Energy Dissipation and Entropy Generation During the Fatigue Degradation: Application to Health Monitoring of Composites

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ENERGY DISSIPATION AND ENTROPY GENERATION DURING THE FATIGUE DEGRADATION: APPLICATION TO HEALTH MONITORING OF COMPOSITES

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

The Department of Mechanical and Industrial Engineering

by

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B.Sc., Isfahan University of Technology, 2005
M.Sc., Iran University of Science and Technology, 2007
December 2014
To my parents, Manouchehr and Mohtaram,

My sisters, Pegah and Baharak, and my lovely wife, Hila
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Abstract

In this dissertation, an experimental approach for characterizing energy dissipation and degradation evolution in a woven Epoxy/Glass (G10/FR4) laminate subjected to fully reversed bending fatigue test is presented. Infrared thermography and acoustic emission are utilized to characterize the degradation progression. The results show similar evolutionary response indicating the presence of three degradation stages.

The effect of the surface cooling on the fatigue life of the laminates is investigated both experimentally and analytically. The results show that the life of the laminate is highly dependent on the temperature and that surface cooling can significantly increase the fatigue life of the laminate.

The signatures of acoustic emission (AE) response emanating from laminates are studied. The distribution of the cumulative AE amplitude is described by a power law. Examination of the evolution of the probability density function (PDF) of the AE energy (counts) reveals two scaling zones wherein the transition from the low energy (count) to high energy (count) regime is identified. The low-energy phase represents very low damage state of the laminate characterized by a power law. The AE energy release and counts follow the statistics and power laws that do not depend on the operational conditions.

A fatigue damage detection method for the laminates based on the cumulative information entropy is reported. The cumulative entropy demonstrates a persistent trend of nonlinear damage evolution typically observed in the experimental measures of the damage in composite materials.

In this dissertation, a continuum formulation for irreversible energy dissipation that accounts for generated acoustic emissions during the loading of the materials is also developed. The evolution of the dissipative energy for AL6061 specimens is experimentally measured as the
material is degraded. A statistically similar behavior is observed in different forms of the dissipated energy as the material degrade.

Finally, a damage detection method for detection of wear in thrust ball bearings coated with molybdenum disulphide (MoS$_2$) is presented. It employs an energy feature obtained from time-frequency representation of the vibration signal. Extensive experimental studies are conducted to verify the efficacy of the proposed method for fault diagnosis of MoS$_2$ coating.
Chapter 1. Overview

1.1 Introduction

Composite materials have gained extensive popularity as an alternative structural material due to their many desirable characteristics. Composites provide high strength and superior performance in a wide range of operating conditions such as load, frequency, environmental conditions including both high/low temperatures as well as corrosive interfaces. Of the different structural configurations pertaining to composites, woven laminates exhibit attractive characteristics such as maintaining the mechanical properties and high damage tolerance. Nevertheless, they are not impervious to degradation and fatigue damage.

This research aims at studying the damage growth and degradation evolution of the woven glass/epoxy subjected to the fatigue. The approach is based on the experimental observation of the laminates subjected to fully reverse fatigue tests. The involving damage mechanisms in the failure of the woven laminates are identified and the corresponding energy dissipation and entropy generation is studied. Once the underlying failure mechanisms are understood, the goal is to identify a feature in the behavior of the laminates that enables us to measure and quantify the damage evolution in the laminates. The outcome of such study leads to design a structural health monitoring scheme. The premise of this dissertation is that fatigue leads to a degradation of the material and that the resulting energy dissipation and entropy generation can be used for characterizing the damage incurred in materials in a non-destructive manner. The following outline summarizes the contents of each chapter of this report.

In Chapter 2, damage mechanisms of the woven glass/epoxy specimens subjected to the fully reverse bending fatigue load are studied and different stages of the damage evolution is
investigated. Two methods of non-destructive tests (NDT) of infrared thermography and acoustic emission are employed to monitor the damage evolution of the specimens.

In Chapter 3, the effect of the environmental factors such as temperature variations on the glass/epoxy coupons subjected to the bending cyclic loading are studied. The performance of the thermography method and acoustic emission are compared in the presence of an air jet that cools the surface of the specimens. The effect of the surface cooling on the life of the specimens is investigated. SEM images taken from the surface of the specimens during the life of the specimens reveals the involved damage mechanisms and their order of appearance in the life of the specimens. To determine the time of the occurrences of the damage modes, different features of the acoustic emission signals are investigated including: counts, average frequency and rise time.

In Chapter 4, statistical analysis is performed on the acoustic emission signals emanating from the coupons during the cyclic loading. Results are presented for AE energy, counts and amplitudes and shown that the distribution of the cumulative AE amplitude can be described by a power law. Further, examination of the evolution of the probability density function (PDF) of the AE energy (counts) reveals two scaling zones wherein the transition from the low energy (count) to high energy (count) regime is identified.

In Chapter 5, a damage detection and health monitoring method is reported that relies on the calculation of the cumulative information entropy from the acoustic emission counts. The cumulative entropy demonstrates a persistent trend of nonlinear damage evolution typically observed in the experimental measures of the damage in composite materials—e.g. dissipated heat energy and loss in elastic modulus.

In Chapters 2-3, the focus is on identifying the damage mechanisms and their corresponding energy dissipation through extensive experimental observations followed by a statistical analysis
in Chapter 4. Following the experimental observations (Chapters 2 through 5), it is the aim of this research to formulate the energy dissipation and entropy generation due to dissipative mechanisms of heat and acoustic emission.

In Chapter 6, a continuum formulation for irreversible energy dissipation and entropy production is developed. Within a thermodynamically consistent framework, the coupling between the mechanical, thermal and acoustic fields is formulated. The evolution of the dissipative energy and entropy production is planned to be experimentally quantified as the material is being fatigued.

In Chapter 7, an energy based condition monitoring scheme for health assessment of the coated ball bearings is also presented. Through monitoring of the vibration energy in time-frequency domain as well as the coefficient of friction, three stages of coating life are identified. They are: healthy period, developing damage, and failure. It is shown that the energy feature can detect whenever wear and damage appear and solid lubricant loses its lubrication capabilities.

In Chapter 8, a brief summary of the conducted research is given. The recommendations for future works are also mentioned.
Chapter 2. Dissipated Thermal Energy and Damage Evolution of Epoxy/Glass using Infrared Thermography and Acoustic Emission*

In this chapter, we present an experimental approach for characterizing degradation evolution in a woven Epoxy/Glass (G10/FR4) laminate subjected to fully reversed bending fatigue test. A fraction of the input mechanical energy during cyclic loading is converted to the thermal energy and consequently the temperature of the material increases. Infrared thermography is used to assess the temperature evolution and identify the structural integrity alterations and various damage states. Acoustic emission is also utilized to corroborate the thermography results in characterizing the degradation progression. The results of these two non-intrusive methods show similar evolutionary response indicating the presence of three degradation stages.

2.1 Introduction

The application of composites as a high-performance engineering material is becoming widespread owing to their high specific stiffness and strength. While parts made of composites are often superior to many other types of materials, they are not immune from degradation and damage. Of particular interest in this paper is to investigate the characteristic of composite material subjected to fatigue brought about by cyclic loading.

Fatigue damage is an irreversible process which deteriorates the material properties and progressively grows toward a critical condition when failure occurs [1-3]. Relevant to composites materials, there are many theoretical and experimental approaches for assessment of fatigue damage [4-49]. Some methods rely on the degradation of Young’s modulus [24-29] to quantify

damage state while others measure dissipated mechanical energy [5, 7, 8, 12, 30, 31] or residual strength deterioration [33-35] to identify damage propagation. Still others use non-destructive testing (NDT) methods to guard against fatigue failure [36-38, 40-46].

Many non-intrusive methods — eddy current, optical holography, ultrasonic resonance, X ray, etc.— are available for detecting voids and defects of the composite material. Among them, for example, acoustic emission (AE) is utilized as an effective damage evaluation technique which detects failure events as they take place. In addition to AE monitoring, infrared thermography (IR) technique is intensively used for the detection of different damage modes [7, 10, 36, 37]. These powerful techniques are also capable of detecting the location where the failure is likely to occur. Nevertheless, a survey of the open literature reveals that the majority of their applications have been limited to primarily tension-compression fatigue studies and fewer studies are available for flexural fatigue damage evolution and their characterization [10, 11].

2.2 Experimental Procedure

The material studied is an unbalanced plain woven Glass /Epoxy (G10/FR4) with plain weave and aligned configuration. The laminate consists of a continuous filament glass cloth with an epoxy resin binder and is stacked in fifteen layers with the thickness of 3 mm. Each woven layer has two unidirectional layers stacked in $[0^\circ/90^\circ]$. Due to high tensile and flexural strength (see Table 2.1), this type of composite finds use in a variety of applications such as electrical equipment, aerospace structures, and rocket structural components. Specimens are prepared with on-axis stacking sequences along the weft directions. In on-axis stacking, the warp and weft directions are aligned with the load direction. The former is called lengthwise ($0^\circ$) while the latter is called crosswise ($90^\circ$).
Table 2.1. Mechanical properties of G10/FR4

<table>
<thead>
<tr>
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<th>Tensile Strength (MPa)</th>
<th>Flexural Strength (MPa)</th>
<th>Elastic Modulus in Flexure (GPa)</th>
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<tr>
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<td>Lengthwise</td>
<td>Crosswise</td>
<td>Lengthwise</td>
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<td>240</td>
<td>380</td>
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<td>18</td>
</tr>
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</table>

Figure 2.1 presents a schematic diagram of the experimental setup for cantilever reverse-bending fatigue tests. The apparatus is a compact bench-mounted unit with a variable speed motor, variable throw crank connected to the reciprocating platen, with a failure cut-off circuit in a control box and a cycle counter. The variable throw crank is adjustable from 0 to 50 mm. For bending fatigue tests, the specimen is clamped at one end and oscillated at the other end with specified amplitude and frequency. Dimensions of the specimen are shown in Figure 2.2. The specimens are manufactured with tapered widths to produce nominally constant stress along the test section in accordance with the ASTM STP standard. High-speed, high-resolution infrared (IR) thermography is used to record the temperature evolution of the specimen during the entire experiment. The IR camera is a MIKRON M7500 with temperature range between 0 °C to 500 °C, resolution of 320 × 240 pixel, accuracy of ±2% of reading, sensitivity/NETD of 0.08 °C at 30 °C, and image update rate of 7.5 Hz. Before fatigue testing, the surface of the specimen is covered with black paint to increase the thermal emissivity of the specimen surface.

The acoustic emission system employed consists of a PCI-2, a two-channel AE system on a PCI card, which is capable of sampling at a rate of 10^6 sample/sec. A wide band, 100-900 KHz, sensor is also mounted on the other side of the specimen. The sensor whose diameter is 19.02 mm is installed on the the specimen (Figure 2.2) and is attached via ECHOGELE grade 30a gel type ultrasonic couplant. The sensor is firmly clamped to the specimen within the experiment. Pre-
amplification of 40 db is applied and recording threshold is set to 45 db. Peak Definition Time (PDT), Hit Definition Time (HDT) and Hit Lockout Time (HLT) are set to 50, 200, 300, respectively. The extracted AE features are counts, counts to peak, and energy. In the following sections experimental results of acoustic emission and Infrared thermography are utilized to study degradation evolution during bending fatigue test.

Figure 2.1 Schematic diagram of the experimental setup in bending

Figure 2.2 Geometry of the specimen used for bending fatigue test. All dimensions are in mm (ASTM STP 566).
2.3 Infrared Thermography

Part (a) of Figure 2.3 shows the average surface temperature recorded using an IR camera (along the dashed line in part (b) of Figure 2.3) versus normalized number of cycles. Normalization \((N/N_f)\) is performed with respect to the number of cycles at failure \((N_f)\).

The specimen (G10/FR4) is subjected to the frequency of 10 Hz and displacement amplitude of 40.64 mm during bending fatigue test. Examination of Figure 2.3 reveals that the temperature evolution undergoes three separate stages: an initial rise (Stage I), slow and steady increase (Stage II), and a drastic increase prior to failure (Stage III). During the first stage, temperature increases due to the occurrence of micro-cracks in multiple locations in the matrix, debonding at the weak interface between fibers and matrix, and the breakage of some fibers with low strength. This stage is limited to a low number of cycles, typically 10-20% of the entire lifespan of the specimen [2, 6, 7, 15-17].

As the fatigue process progresses, the crack density in the matrix reaches a “saturation level,” where the damage growth becomes stable. The existing cracks grow to the fiber/matrix interface
where cracks cannot cross the high strength fiber and bifurcate in two directions. In the third phase, which lasts approximately 10-20% of the entire lifespan, the temperature rises rapidly after a comparatively small number of cycles until failure occurs due to fiber breakage.

### 2.4 Acoustic Emission

Figures 2.4, (a) and (b), show the cumulative counts to peak and cumulative energy of the acoustic emissions plotted versus the normalized number of cycles (normalized with respect to number of cycle at failure) for two bending fatigue tests with displacement amplitude of 35.56 mm and 38.1 mm and a frequency of 10 Hz. The counts to peak is defined as the number of AE counts between the beginning of the AE hit and its peak amplitude and the energy is obtained via integration of rectified voltage signal over the duration of the signal. The results of these figures also reveal three distinct emission regimes. In the first stage (Stage I of Figures. 2.4 (a) and (b) the AE events belong to cyclic deflection of the laminate as well as weak points of the material from all parts of the specimen.

The duration of the first stage depends on load level of the experiment and lasts about 10-20% of the total life. Eventually as more cycles pass, the interface between the fibers and matrix breaks and matrix cracking occurs (Stage II of Figures. 2.4 (a) and (b)). Higher applied loads reduce the duration of this stage. The second stage, which incorporates a major fraction of the component life, has a positive slope whose value depends on the number of acoustic events. The third stage, in which fiber breakage occurs, is associated with the high rate of acoustic events and continues until the complete failure of the component.

### 2.5 Comparison of Acoustic Emission and Thermography

Figures 2.5 (a) and (b) compare the temperature profile and AE cumulative counts. This experiment is carried out on a Glass/Epoxy laminate at the frequency of 10 HZ and displacement
amplitude of 38.1 mm. The results of both AE and thermography exhibit a similar trend. In both cases, the Stage I lasts for an approximately 20% of the total life.

Figure 2.4 (a) AE Cumulative counts to peak vs. Normalized number of cycle (normalized with respect to the number of cycle at failure) of Epoxy/Glass laminate at frequency of 10 HZ and displacement amplitude of 35.56 mm. The short stage (Stage I) of AE counts to peak is followed by a relatively steady increase with a suddenly rise close to the failure. (b) AE Cumulative energy vs. Normalized number of cycle of Epoxy/Glass laminate at frequency of 10 HZ and displacement amplitude of 38.1 mm.
Figure 2.5 Surface temperature evolution, (a) and AE cumulative counts, (b) respect to the normalized number of cycle for 92% of total life. The results of both AE and IR thermography demonstrate the same damage evolution trend.

Part (a) of Figure 2.6 shows Scanning Electron Microscopy (SEM) image of the surface of the specimen during the first stage. As the operation continues, more numbers of acoustic events exceed the threshold and as a result the cumulative counts increase. Such events represent matrix cracking and delamination within the laminate. The transition from Stage I to II, can be easily observed from the rate of the temperature and AE cumulative counts.

To further distinguish the nature of damage in different stages, an SEM image of the surface of the specimen from the second stage of the laminate’s life is presented in Figure 2.6 (b) in which
matrix cracking and separation of matrix and fiber is detectable. This image is taken at 40% of the total life. Transition to Stage III occurs when the cumulative number of cycles approaches 90% of the total life. This can be easily recognized from temperature profile and cumulative AE counts plots in Figures 2.5 (a) and (b). The SEM image of the surface of the specimen from the final stage, Figure 2.6 (c), depicts the fibers breakage of the laminate considered as a severe damage of the composite component. After the 90% of the total life, the amount of emissions severely increases.

![SEM images of Epoxy/Glass](image)

Figure 2.6 SEM image of the surface of Epoxy/Glass during different stages of fatigue life. (a) 5% fatigue test (Stage I). (b) 40% of total life (Stage II). (c) 90% of fatigue life at which temperature profile and acoustic behavior shoot up due to fiber breakage and macro-crack growth (Stage III).
2.6 Conclusions

In this study, dissipated energy and damage accumulation is characterized using the infrared thermography technique for fully reversed bending of Epoxy/Glass. Acoustic emission technique is also used as a damage detection technique to verify the dissipated energy evolution and damage process. The temperature results in characterizing the degradation progression is corroborated by AE results and both methods show the damage evolution in a same manner. The results indicate the existence of three distinct stages during the lifespan of the laminate. The first of which is healthy period of almost 20% of the total life. In this phase of operation matrix cracking occurs at weak points of the material. A second stage is observed in which debonding and fiber matrix delamination take place. The final phase of operation is along with an abrupt temperature and acoustic descriptors increase due to fiber breakage and continue until the complete failure of the component. SEM images captured at three stages, in different cycles of operation, show the damage growth during degradation.

2.7 References


Chapter 3. On the Role of Cooling on Fatigue Failure of a Woven Glass/Epoxy Laminate*

In this chapter, the effect of the surface cooling on the fatigue life of a Glass/Epoxy laminate during fully-reversed bending tests is investigated both experimentally and analytically. The experimental tests involve the use of acoustic emission and infrared thermography to monitor the structural integrity and the evolution of damage. An analytical study is also performed to calculate the stress in the outermost layer of the laminate for both cases of cooled and uncooled specimens. The results show that the life of the laminate is highly dependent on the temperature and that surface cooling, if done appropriately, can significantly increase the fatigue life of the laminate.

3.1 Introduction

Composite materials are employed as an alternative to metals due to their high strength and superior performance in a wide range of the operating conditions such as load and frequency as well as different environmental conditions such as high humidity, corrosive interfaces, and high temperature, etc. Nevertheless, they are not impervious to fatigue. Degradation processes are accompanied with dissipative phenomenon such as acoustic emissions and heat generation. Both of the environment temperature and temperature rise is reported to significantly affect the fatigue life of the composites under cyclic loading [1-6]. Therefore, non-destructive methods for in-situ monitoring of their integrity via acoustic emission sensors [7-11] and infrared thermography [12-16] are employed to study the damage evolution of the laminates. In addition to non-intrusive methods, there are fatigue damage approaches to model the degradation of the materials. One of the approaches in fatigue analyses common to metals and composite laminates is the use of the

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stress data and interpretation of the stress behavior plotted as a function of the number of cycles (the so-called S-N curves) [1]. Another approach—a phenomenological method [1]—makes use of the remaining strength of the laminate subjected to repetitive loading to assess fatigue life. In a phenomenological method, a damage parameter is defined to describe the reduction of stiffness or strength. The third approach is the so-called “progressive model,” which is based on predicting the damage growth as well as predicting the remaining mechanical properties using quantifiable damage variables such as delamination and matrix crack size or strength [1]. While advances are being made, experimental results and modeling approaches that can realistically assess the role of the operating conditions on the fatigue life of composites are scarce.

This paper aims to investigate the effects of operating conditions on the mechanical properties and the fatigue life of Glass/Epoxy laminates. In this research, acoustic emission and infrared thermography are employed to monitor the signs of damage accumulation as manifested in generating strain waves (acoustic emission) and increase in the surface temperature. The outline of this paper is as follows. A description of the material and the experimental apparatus is presented in Section 3.2. Section 3.3 investigates the effects of the surface cooling on the fatigue life of the Glass/Epoxy laminate by means of infrared thermography and acoustic emission. In Section 3.4, the results are corroborated by scanning electron microscopy (SEM). This is followed by Section 3.5 where the acoustic emission features including average frequency and rise time are investigated. In Section 3.6, an analytical method is employed to calculate the stress in the outermost layer of the laminate. Section 3.7 contains the concluding remarks.

3.2 Material and Experimental Procedure

The material tested is Glass/Epoxy (G10/FR4) which is an unbalanced woven fabric composite with plain weave and aligned configuration. The laminate is stacked in fifteen layers
within the thickness of 3 mm. Each woven layer has two unidirectional layers stacked in [0º/ 90º] made of continuous filament glass cloth in epoxy resin binder.

Part (a) of Figure 3.1 shows the schematic of two layers of plain-woven Glass/Epoxy with aligned configuration. Part (b) of Figure 3.1 shows the schematic of specimens manufactured based upon ASTM STP 566 for use in reverse-bending fatigue tests. Specimens are prepared with on-axis stacking sequences. In on-axis stacking, the warp and weft directions are aligned with the load direction. The former is called lengthwise (0º) while the latter is called crosswise (90º). The crosswise and lengthwise elastic modulus in flexure of G10/FR4 is 15.1 MPa and 18.6 MPa, respectively. The crosswise and lengthwise flexural strength is 310 MPa and 379 MPa, respectively.

![Figure 3.1](image)

Figure 3.1 (a) Schematic of the woven Glass/Epoxy laminate. (b) Geometry of the specimen used for bending fatigue test (All dimensions are in mm).

A schematic of the experimental apparatus employed in this research is shown in Figure 3.2. It consists of a bench-mounted unit containing a variable speed motor, variable throw crank connected to the reciprocating platen with a failure cut-off circuit in a control box and a cycle counter. The crank can be tuned from 0 to 50 mm to apply bending displacement. The specimen is clamped at one end and the other end is oscillated with a specified amplitude and frequency.
Surface cooling is provided using a vortex tube that blows air directly on the reduced cross section area of the specimen at two specified rates of 2.23 and 4.93 (J/s), cooling the surface to 15 °C and 6 °C, respectively. The cooling rate of air on the specimen surface, $Q$, is calculated based on the mass flow rate of the air jet and its temperature, i.e., $Q = \rho V A C_p (T_{out} - T_0)$, where $\rho$ is the air density and equals to 1 Kgm$^{-3}$, $V$ is the air velocity, $A$ represents the cross sectional area of the vortex tube equals to $32.069 \times 10^{-6} \text{ m}^2$, $C_p = 1.0065 \text{ KJkg}^{-1}\text{K}^{-1}$ is the specific heat of air, $T_{out}$ denotes the temperature of outlet air and $T_0$ is the room temperature. The air velocities of the two different cooling rates are 6.1 and 4.8 m/s.

Temperature is measured by means of a high-resolution infrared (IR) thermography camera (MIKRON M7500) capable of measuring temperature within the range of 0 °C to 500 °C. The resolution is $320 \times 240$ pixel with an accuracy of ±2% of the reading. The sensitivity of the IR-camera is 0.08 °C at 30 °C and it updates the image at a rate of 7.5 Hz. The thermal emissivity of the specimen is increased by painting its surface in black.

A PCI-2, a two-channel AE system, continuously measures the acoustic emissions from the specimen during the entire test. It samples up to a rate of 10 MHz. A wide-band sensor, 19.02 mm in diameter (range: 100-900 kHz), is mounted on the clamped side of the specimen as shown in Figure 3.2. Gel-type ultrasonic couplant is used to attach the sensor to the specimen. Pre-amplification and recording threshold are set to 40 dB and 45 dB, respectively. Peak Definition Time (PDT), Hit Definition Time (HDT) and Hit Lockout Time (HLT) are specified as 50, 200, and 300, respectively. The extracted AE features are: counts, rise time, counts to peak, duration and average frequency; The time from the first threshold passing to the end of the last threshold passing is called “Duration” while the number of AE signals which exceeds the threshold level is called “Counts.” The average frequency over the entire AE hit (in kHz) is recognized as the
“Average Frequency” and is defined as the AE counts over the duration. The time from the first threshold passing to the maximum amplitude of the AE signal is called the “Rise time.”

![Figure 3.2 Schematic diagram of the experimental setup in bending](image)

### 3.3 Temperature and Acoustic Response of the Specimen

A series of fully reversed bending fatigue tests is performed with and without cooling in order to examine the role of surface cooling on the fatigue life of the laminate and to show the possible correlation between temperature and acoustic emission response. The tests are performed in three frequencies (7, 10, and 15 Hz) and in three displacement amplitudes (38.1, 41.91 and 43.18 mm). A persistent trend observed in all experiments conducted is a three-stage damage evolution as illustrated in Figure 3.3 [17].

![Figure 3.3. Three regions of damage accumulation in a woven composite.](image)
Matrix cracks are initiated in Stage I and grow as in Stage II where cracks coalesce and the damage occurs at the matrix-fiber interface. Consequently, damage accumulates and stiffness is reduced. In Stage III, the major damage mechanism is fiber breakage which ends in the failure of the specimen where it breaks into two pieces. However, fiber breakage is not specific to Stage III and may start earlier as well. The results of the two sample experiments are presented in Figure 3.4 to demonstrate the correlation between the temperature and AE response of the specimen. Figures 3.4 (a) and (b) show the results of temperature and cumulative AE counts of two fatigue tests at displacement amplitude of 41.91 mm and frequency of 10 Hz. In Figure 3.4 (b), a cooling rate of 4.93 (J/s) is applied to the surface of the specimen during the fatigue test. The response of the specimens to cyclic loading—with or without cooling—consistently yields the three-stage trend depicted in Figure 3.3.

![Figure 3.4](image)

**Figure 3.4.** The surface temperature (right) and the cumulative AE counts (left in log scale) vs. time of Glass/Epoxy laminate at frequency of 10 HZ and displacement amplitude of 41.91 mm. a) without surface cooling. b) With cooling rate of 4.93 (J/s).

Generally, the duration of each stage depends on the operating conditions including the displacement amplitude, frequency and the cooling rate. The results of the thermography and acoustic emission show similar trends, i.e. a rapid increase in the first part of the test (Stage I)
followed by a more gentle increase (Stage II) and finally a rapid increase (Stage III) leading to the final failure. A similar trend is observed in temperature profile of a laminate of the same material (G10/FR4) under tension-tension test with a zero load ratio and for both on-axis and off-axis loading directions.

Examination of the results reveals that the cooled specimen (Figure 3.4 (b)) lasts remarkably longer than the uncooled one (Figure 3.4 (a)). Figure 3.4 (b) shows that in the presence of cooling, the temperature does not vary during the test until the final stage where the specimen fails. However, in the absence of cooling (Figure 3.4 (a)) temperature profile rises steadily and damage accumulates. Since in the experiments with cooling, the transition from Stage II to III cannot be clearly identified from the temperature profile (Figure 3.4(b)), the AE signature is utilized to determine the state of the damage in the experiments with cooling. The response of the infrared thermography commences when fiber fracture associated with plastic deformation and pull-out events occur [18-20]. The infrared thermography also determines the damage zone as well as the damage and the crack growth stages [18, 19]. However, in addition to damage formation and propagation zones, AE signals are emitted from dissipation processes where fiber/matrix debonding dominates [18, 19]. See further discussion about the type of the damage in each stage in Section 3.4.

3.4 Scanning Electron Microscopy (SEM) of the Glass/Epoxy Laminate

When a woven type of Glass/Epoxy laminate is subjected to fatigue loading, the initial surface damage starts from the crossover points where wefts cross the warps. These early surface cracks are perpendicular to tension direction. Figure 3.5 shows a schematic of the location where these initial cracks appear as well as an SEM image of the surface where the wefts cross over the warps. The cracks in the matrix, when subjected to further cyclic loading, move toward each other and
result in a matrix failure in the later stages of the test. Fibers are also susceptible to cracks in the last stage of the laminate’s life.

Figure 3.5. The schematic of the location where these cracks appear as well as a SEM image of the surface.

Figures 3.6 and 3.7 compare the surface of the specimen in different stages of its life subjected to 10 Hz frequency and the displacement amplitude of 41.91mm. In order to demonstrate the role of cooling on delaying the damage formation, four experiments with cooled and uncooled conditions are performed. In the first two experiments, the tests are stopped during the Stage I and the specimens are examined using an SEM. The results of these two tests are shown in Figs 3.6 (a) and 6 (b), respectively. Figure 3.6 (a) shows visible surface cracks in the test without cooling while the surface of the specimen with the cooled specimen (Figure 3.6 (b)) appears to be pristine. It can be concluded that cooling provides resistance to the initial surface cracks in the first stage of the operation.

Since the accumulated damage is appreciable in Stage III, it was decided to halt the uncooled test in Stage III after 2000 cycles (Figure 3.7(a)). Figure 3.7(b) shows the cooled specimen interrupted after 2000 cycles in Stage II.
Figure 3.6 SEM images of the cooled and uncooled surface of the specimens. (a) The surface of the specimen in Stage I of its operation without cooling. The image is taken at the number of cycle=9. (b) The surface of the specimen with cooling in Stage I of its operation. The image is taken at beginning of the test (number of cycle=9).

Figure 3.7. (a) The surface of the un-cooled specimen in Stage III of its operation. The image is taken when the temperature tends to rise (without cooling) and after 2000 Cycles. (b) The image of the surface of the cooled specimen after passing 2000 cycles (in Stage II of its operation). The surface cooling is applied from start of the test. (c) Crack crossing on the surface of the specimen in stage III of its operation. The SEM image is taken when the temperature begins to rise and cooling is not provided in this test.
Figure 3.7 (a) shows that the cracks in the weft direction have coalesced and the cracks in the warps direction appear on the surface. In contrast, the cooled surface appears to be less degraded during the same number of cycles (Figure 3.7 (b)). In Figure 3.7(c), severe damage associated with crack crossing is observed which eventually leads to delamination in the Stage III of the experiment without cooling.

The composite coupons subjected to cyclic loading generate an appreciable amount of heat in the deformed zone within which the crack growth is accelerated. High frequency of applying load which is equivalent to higher rate of applying work is a reason that the generated heat traps inside the laminate [21]. Another reason for increasing temperature in the composite laminates is stress concentration which is reported by Takahara et al.[22] in the study of glass fiber reinforced poly(butylene terephthalate) (PBT) fatigue life. The dissipated mechanical energy converted to heat progressively damages the specimen if it is not extracted at the same rate generated. The surface cooling removes the accumulated heat and delays the thermal softening within the thermoset material.

Similar effects on the fatigue life improvement is also reported by Cessna et al. [23] in a short glass fiber-reinforced and unreinforced thermoplastics. Controlling the temperature of specimens delays the stiffness fall until to the cycles close the failure [23]. The adverse effect of the generated heat on the fatigue life of the fiber reinforced composites is more significant in high frequency cyclic loadings. The reason is that in the high frequency applications both of the generated heat per cycle and stored heat inside the laminates increase with the rise of the cyclic loading frequency [21]. In general, the damage mechanisms of a woven composite laminate are matrix cracking, delamination, fiber breakage and debonding of fibers and matrix [24-26]. The occurrence of these
mechanisms can be detected by the acoustic emission descriptors since emissions are depended upon the severity of the faults and the type of the damage.

Figure 3.8 shows the evolution of the acoustic emission counts in an experiment with displacement amplitude of the 43.18 mm, the frequency of 7 Hz and without cooling. Also shown are SEM pictures at various stages of the evolution. The increase in the severity of the damage is apparent in the number of counts of the acoustic emission signals.

Figure 3.8. The counts plot of an experiment carried under load amplitude of the 43.18 mm and frequency of 7 Hz without cooling. The types of the damages appeared on the surface of the laminate in different number of cycles are shown.

The emissions can be divided into three distinct categories each belonging to a specific type of damage. Matrix cracks are the result of the early stage damage that lead to crack coupling and further damage. Side edges of the laminate are susceptible to delamination because of the significant interlayer stresses. Additionally, matrix cracks and fiber breakage inside the laminate cause high interlaminar stresses, which ultimately result in delamination. Generally, fiber breakage does not occur unless the load or the strain exceeds a certain critical level. However, fiber breakage
can take place in the early stages of the fatigue loading in weaker fibers or in the presence of the stress concentration in the matrix cracks.

3.5 Average Frequency and Rise Time of the Acoustic Emission Signals

Figures 3.9 and 3.10 show the results of two experiments with/without cooling and depict the evolution of the AE signals in the form of the average frequency. The duration of the test until the failure of the specimen in the experiment without cooling is 240 (s) and in experiments with a cooling rate of 2.23 (J/s) is 800 (s). In both experiments, the average frequency of the acoustic emission signals in Stages I and II is almost 100 Hz and the average frequency in Stage III is 220 Hz. The average frequency feature of the acoustic signal conveys information regarding the frequency of the AE events and can represent the type and severity of the damage. This descriptor of the AE signals is calculated from the number of thresholds passing of the signal over the duration. In the experiments performed at different operating conditions including the displacement amplitude, frequency and surface cooling, a persistent behavior of an apparent increase in the average frequency at the end of the Stage II is observed. Referring to Figure 3.9, it can be observed that the time interval of the [0-175 s] is accompanied with acoustic emissions of an average frequency equal to 100±10 kHz. During the time interval of the [175 -240 s], the observed average frequency increases to 220±10 kHz. In the experiment with cooling (Figure 3.10), the intervals [0-280 s] and [280-800 s] have average frequency of 100±10 kHz and 220±10 kHz, respectively. In previous sections, the sequence of the damage progression and degradation was discussed and it was shown that the dominant damage modes in the first two stages of the life of the specimen are matrix cracking and debonding. In Stage III the fiber breakage and pull out events, indicative of severe permanent deformations, are the main damage mechanisms involved.
It can also be assumed that in Stage III, when the rupture occurs in the matrix and the cracks move toward the surface, the separated matrixes are in relative contact.

Figure 3.9. Average frequency of the acoustic emission signal. The experiment is of 41.91 mm amplitude and a frequency of 10 Hz without cooling.

Figure 3.10. Average frequency of the acoustic emission signal. The experiment is of 41.91 mm amplitude and a frequency of 10 Hz and a cooling rate of 2.23 (J/sec).
In this stage, because of the ruptured matrixes fibers experience higher loads and this leads to fiber breakage. Consequently, analogous interactions occur between the broken fibers. The damage mechanisms in Stage III as well as the interactions between the broken fibers and matrix are responsible for the increase in average frequency of the acoustic emission signals in transition from Stage II to Stage III. The emissions with average frequency under 100 kHz have higher rise time while the acoustic emission events of higher average frequency have a lower rise time, as shown in the histogram in Figure 3.11. This can be attributed to the type of the failure which occurs in each stage.

![Rise Time vs Average Frequency](image)

Figure 3.11. The rise time of the AE signals versus average frequency for a test of the load amplitude of 41.91 mm.

The low average frequency (under the range of 100±10 Hz) and higher rise time are indicative of internal friction of the laminate, debonding and matrix cracking in the first two stages of the operation. However, as the damage develops, the emissions exhibit a higher average frequency and lower rise time, due to the fiber breakage. Momon et al.[27] also reports that in the fatigue experiments of the ceramic matrix composites (CMC), signals of higher rise times are observed
due to the matrix cracking and there is a class of signals with a lower rise time whose sources are the fiber breakages and more severe type of the failure.

3.6 Stress Analysis of the Laminate

To gain further insight into the effect of cooling on the strength of the laminate, an analytical model is developed to analyze the behavior of the cantilever-type bending fatigue tests. Figure 3.12 (a) shows a schematic of the model corresponding to the specimen shown in Figure 3.1 (b). Figure 3.12 (b) and (c) depicts the one-to-one correlation for whole fatigue life and the stiffness degradation. The laminate is clamped at one end and at the other end it is connected to an actuator that oscillates at the imposed displacement amplitude $u_2$. The magnitude of force which imposes the maximum bending displacement amplitude $u_{max}$ is calculated using the virtual work principle from the following equations.

$$u_1 = F \int_0^{L_1} \frac{(L_1 - x)^2}{I(x)} \, dx + FL_2 \int_0^{L_1} \frac{(L_1 - x)}{I(x)} \, dx$$  \hspace{1cm} (1)

$$\alpha = F \int_0^{L_1} \frac{(L_1 - x)}{I(x)} \, dx + FL_2 \int_0^{L_1} \frac{1}{I(x)} \, dx$$  \hspace{1cm} (2)

where $F$ is the force, $\alpha$ is the slope of the oscillating clamp at point A in Figure 3.12 (a), and $I(x)$ presents the bending stiffness of the cross section. Referring to Figure 3.12 (a), the relationship between the maximum displacement amplitude and displacement at point A is:

$$u_{max} = u_2 = u_1 + L_1 \sin(\alpha)$$  \hspace{1cm} (3)

In displacement-controlled bending fatigue test, the applied force is not constant and decreases during the test. To determine the magnitude of the bending force, equations (1) and (2) is substituted into equation (3) and the resulting equation is solved for $F$. With the force determined, the moment $M$ is obtained using equation (4). The resulting expression is:

$$M(x) = F.(L_1 + L_2 - x)$$  \hspace{1cm} (4)
The strains and stresses are then calculated as follows:

\[ e_x(x, y) = \frac{M(x)(y - y_0)}{I(x)} \]  
(5)

\[ S_x = E_0(1 - D(x, y))e_x(x) \]  
(6)

where \( y_0 \) is the position of neutral axis, \( E_0 \) presents the modulus of the beam, \( D(x, y) \) is the damage value. The degraded bending stiffness is calculated as in equation (7):

\[ I(x) = b(x)E_0 \int_{-y/2}^{y/2} (1 - D(x, y))y^2dy \]  
(7)

where \( b(x) \) is the width of the laminate and \( t \) represents the laminate thickness.

A similar calculation to assess the laminate stress and fatigue damage evolution is reported by Van Paepegem [28-31]. The simulation procedure is given as follow.

1- Solve \( F \) from equations (3) and (4).

2- Calculate moment, strain, stress, and bending stiffness from equations (4) to (7).

3- Update \( u_I \) and \( \alpha \) using equations (1) and (2), respectively.

4- If the number of cycle is less than the number of cycle to failure, an incremental number of cycles is applied and return to step 2. Otherwise, stop the procedure.

In the present study, we utilize the results of the acoustic emission to calculate the stress in the outermost layer of the laminate based on the work of Williams and Reifsnider [32] who
attempted to correlate acoustic emission counts to the compliance of a composite laminate. They showed that there exists a nearly one-to-one correspondence between the compliance and AE counts up to the point where significant damage takes place. The last stage of the test is associated with severe matrix cracking, cracks crossing and fiber breakage until failure occurs. When the fibers break, the friction between the broken yarns as well as in between the separated matrix induces a large amount of measureable AE signals. Therefore, the AE counts increase at a higher rate than that of rise in the temperature. Specifically, the AE is more sensitive to the severity of the damage during the last stage of the operation in comparison to the thermography tests and manifests itself as a rise with a higher slope.

Typically, laminate failure is considered to occur when the stiffness is reduced to 60-80% of its initial stiffness [33]. Utilizing the average of 70% of reduction in stiffness, one can develop a model to approximately correlate the acoustic emission and stiffness or compliance of the laminate. Figure 3.12 (b) shows the typical stiffness degradation (\(E'\)) calculated from the one-to-one correlation with the AE counts. By noting that at the beginning of Stage III stiffness reduction is not as rapid as the acoustic emission and considering an average 70% of reduction in stiffness as the final value for stiffness, one can correlate the stiffness reduction shown in Figure 3.12 (b) to the stiffness reduction (\(E\)) in the form of Figure 3.12 (c) using the following expression.

\[
E(N) = E'(N) \quad \text{if } N < N_f
\]

\[
E(N) = E_f + \frac{E_f - E_0}{E_0} E'(N) \quad \text{if } N > N_f
\]

The results of stiffness degradation of Figure 3.12 (c) are utilized to estimate damage values as follows:

\[
D = \frac{E - E_0}{E_f - E_0}
\]
The above analytical procedure is implemented in MATLAB™ software package and applied to all of the experiments performed under the frequency of 10 Hz to calculate the stress in the outermost layer of the laminate during the cyclic loading at the end of the Stages I and II. Figure 3.13 demonstrates the stress versus the number of cycles (S-N curve) of 12 experiments including no cooling as well as with two cooling rates of 2.23 and 4.93 (J/s). Hollow symbols represent the stress in the outermost layer of the laminate at the end of the Stage I and solid marks represent the strength at the end of the Stage II. By moving from the end of the Stage I to the end of the Stage II, damage occurs and intensifies in the laminate. Consequently, the stress of the laminates reduces significantly which is apparent in the Figure 3.13.

![Figure 3.13. Comparison of the stress in the outermost layer of the laminate during the fatigue life for with and without cooling.](image)

The effect of the surface cooling on the fatigue life of the laminate is shown in the Figure 3.13 for two cooling rates of 2.23 and 4.93 (J/s). It is apparent that the experiments with surface cooling can function over more number of cycles and last longer than the experiments without surface cooling. It is also revealed that under the test conditions of the present work, a higher cooling rate
results in a higher strength in the laminate. It should be noted that the degradation and deterioration process in a polymer matrix laminate is highly dependent on the temperature and generally higher temperatures lead to a greater degradation. In the experiments without cooling, the generated cyclic heat remains inside the laminate and accelerates the damage accumulation and results in a rapid failure. Table 3.1 summarizes the calculated stress of the laminate in two stages of its life (Stage I and II) and for displacement amplitudes of 38.1, 40.64, 41.91 and 43.18 mm, frequency of 10 Hz, and two cooling rates of 2.23, 4.93 (J/s) and no cooling.

Table 3.1. A summary of calculated stress of the laminate

<table>
<thead>
<tr>
<th>Load amplitude</th>
<th>Cooling rate (J/s)</th>
<th>Stress at the end of Stage I (MPa)</th>
<th>Stress at the end of Stage II (MPa)</th>
<th>Number of cycles at failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>38.1</td>
<td>No cooling</td>
<td>187</td>
<td>165</td>
<td>6800</td>
</tr>
<tr>
<td>38.1</td>
<td>2.23</td>
<td>187</td>
<td>150</td>
<td>15400</td>
</tr>
<tr>
<td>38.1</td>
<td>4.93</td>
<td>187</td>
<td>155</td>
<td>22000</td>
</tr>
<tr>
<td>40.64</td>
<td>No cooling</td>
<td>195</td>
<td>160</td>
<td>4000</td>
</tr>
<tr>
<td>40.64</td>
<td>2.23</td>
<td>200</td>
<td>172</td>
<td>8600</td>
</tr>
<tr>
<td>40.64</td>
<td>4.93</td>
<td>206</td>
<td>187</td>
<td>9500</td>
</tr>
<tr>
<td>41.91</td>
<td>No cooling</td>
<td>205</td>
<td>170</td>
<td>2600</td>
</tr>
<tr>
<td>41.91</td>
<td>2.23</td>
<td>206</td>
<td>178</td>
<td>8100</td>
</tr>
<tr>
<td>41.91</td>
<td>4.93</td>
<td>200</td>
<td>179</td>
<td>10000</td>
</tr>
<tr>
<td>43.18</td>
<td>No cooling</td>
<td>210</td>
<td>180</td>
<td>2500</td>
</tr>
<tr>
<td>43.18</td>
<td>2.23</td>
<td>214</td>
<td>194</td>
<td>7500</td>
</tr>
<tr>
<td>43.18</td>
<td>4.93</td>
<td>214</td>
<td>202</td>
<td>9000</td>
</tr>
</tbody>
</table>
3.7 Conclusions

Fully reversed bending fatigue tests were performed to characterize the damage accumulation of a woven Glass/Epoxy laminate with the application of external cooling. The cyclic deflections are applied in the end of the cantilevered beam and the temperature variations and acoustic emissions were measured from specimen. The primary results are the existence of three distinct stages during the lifespan of the laminate. The first of which is almost 20% of the total life where matrix cracking occurs at weak points of the material. A second stage is observed in which debonding and fiber matrix delamination take place. The final stage of operation manifests itself in the form of an abrupt increase in the temperature and the acoustic descriptors due to fiber breakage and continues until the failure occurs. SEM images captured at different experiments with and without cooling at two stages of the operation show less severe damage exists in the case when surface cooling is applied.

Acoustic emission and surface temperature evolution show a close dependency on the rate of the applied work as well as the heat removal from the laminate. It is shown that the surface cooling of the Glass/Epoxy delays the failure of the laminate remarkably.

The damage states can be characterized from the examination of the average frequency of the AE events. In our experiments, the average frequency of 100 kHz is detected in a state of a laminate of less severe damage. As the damage develops within the laminate from a minimal matrix cracking to crack coalescing, delamination and fiber breakage, the average frequency of the AE signals gradually increase up to a value of 220 kHz in the last moments of its life span. An analytical procedure is performed to calculate stress in the outermost layer of the laminate which incorporates the acoustic emission counts to calculate the degraded strength. The results show that
in the case of surface cooling, the strength of the laminate is significantly increased comparing to the cases where cooling does not exist.

3.8 References


Chapter 4. Criticality of Degradation in Composite Materials Subjected to Cyclic Loading*

Degradation of composite materials subject to cyclic loading is a multi-step process involving micro-cracks formation and progression until failure occurs. In this paper, the signatures of acoustic emission (AE) response emanating from composite specimens subjected to fully-reversed bending fatigue are studied. The composite is glass/epoxy (G10/FR4) laminates and the experiments cover different frequencies and displacement amplitudes. Results are presented for AE energy, counts and amplitudes. It is shown that the distribution of the cumulative AE amplitude can be described by a power law. Further, examination of the evolution of the probability density function (PDF) of the AE energy (counts) reveals two scaling zones wherein the transition from the low energy (count) to high energy (count) regime is identified. The low-energy phase represents very low damage or damage-free state of the laminate characterized by a power law. In these series of experiments, AE energy release and AE counts follow the statistics and power laws that do not depend on the operational conditions.

4.1 Introduction

Recent research on the fracture of heterogeneous materials at the micro level [1] shows that the advancement of degradation is accompanied with bursts that follow a universal power-law distribution [2]. Decaying power laws are observed in the response of materials—in both simulations and experiments—subjected to the loading- and straining procedures [3-10].

Irrespective of the type of loading and the underlying damage mechanisms, material degradation is always accompanied with dissipation of strain energy [11-15]. A portion of this

* This chapter previously appeared as Kahirdeh A, Khonsari MM, Criticality of degradation in composite materials subjected to cyclic loading, Composite Part B Engineering, Vol. 61, pp. 375-382. It is reprinted by permission of the Elsevier. See Appendix 1 for the permission letter.
released energy is in the form of the acoustic emissions which itself is a subcategory of a broader phenomenon called the crackling noise [16-18]. This phenomenon is known to occur in diverse range of systems including paper crumpling [19], Barkhausen magnetic noise [20], earthquakes [21], systems with interfacial and sliding friction [22], intermittent plastic flow [23] and fracture of materials [24, 25]. Recent research shows that AE signals emanating from fracture of different materials exhibit a behavior that can be described by decaying power law distribution [26-32]. For example, experiments on polyurethane foams conducted by Deschanel et al.[26] reveal that AE energy in creep and tensile experiments can be characterized by power law. Experiments dealing with fracture of paper samples with a small notch in tensile tests by Salminen et al.[27] also revealed that the energy distribution of AE signals exhibit a power law with an exponent of α=-1.25. Similarly, the burst distribution in propagation of the interfacial crack along the weak plane of a block of Plexiglas is reported to follow a power law distribution with α=-1.7 [28]. The crackling dynamics observed in [28] was later modeled by Laurson et al.[29] and Bonamy et al. [30] who classified this phenomenon as a self-organized critical phase transition [30].

The observation of the power-law behavior associated with the AE signatures is not confined to problems involving fracture and crack propagation. It is also seen in plastic deformation and dislocation dynamics of crystalline materials. For instance, the energy of the acoustic emissions measured from single ice crystals under constant-stress creep tests exhibit a decaying power law with α=-1.6 [6]. The applicability of power law in characterizing acoustic emission appears to be scale free and independent of the details of the system. While the AE signature associated with the fracture of diverse array of materials are known to exhibit scale-free trend, relevant information on the behavior of materials subjected to cyclic fatigue loading is scarce. It is of interest to exploit the evolution of the acoustic emissions in the degradation of materials with micro-fracture(s) due
to cyclic fatigue. For this purpose, woven glass/epoxy laminates are examined by means of AE. We seek to determine if there exists a scaling function which holds throughout the life of the laminates for different operational variables. We also present statistical behavior of AE features to examine the applicability of the concept of self-organized criticality to the fatigue fracture of the laminates.

4.2 Material

Specimens tested are made of Glass/Epoxy (G10/FR4) —an unbalanced woven fabric composite with plain weave-and-aligned configuration— stacked in fifteen layers within the thickness of 3 mm. The structure of this type of composite is formed by interlacing two sets of orthogonal yarns (warp and weft) as shown in Figure 4.1 (a). Two unidirectional layers stacked in [0°/ 90°] made of continuous filament glass cloth in epoxy resin binder form each woven layer. The specimens are prepared with on-axis stacking sequences in which warp and weft directions are aligned with the load direction. They are manufactured based upon the ASTM STP 566 for use in reverse-bending fatigue tests with a similar configuration reported in [33, 34]. For a detailed description of the woven types of composites refer to [35]. The G10/FR4 crosswise elastic modulus and the lengthwise elastic modulus in flexure are 15.1 MPa and 18.6 MPa, respectively. The crosswise and lengthwise flexural strength are 310 MPa and 379 MPa, respectively. A woven composite laminate has internal defects in both macro- and micro-scale due to its specific structure and manufacturing procedure (Figure 4.1 (b)). From a chronological perspective, in the tested woven glass/epoxy, the initial surface damage starts from the crossover points where wefts cross the warps and results in micro crack advancement and coalescence. Hence, this layered material is susceptible to debonding and interlayer stress concentration.
4.3 Experimental Procedure

4.3.1 Apparatus and Data Acquisition

The description of the bending fatigue apparatus is reported elsewhere [33]. Briefly, the specimen is clamped at one end and the other end is oscillated with a specified amplitude and frequency. A PCI-2, a two-channel AE system which samples up to a rate of 10 MHz, measures the acoustic emissions from the specimen during the entire test, i.e. until failure occurs.

![Figure 4.1](image)

Figure 4.1 (a) Plain weave pattern of each layer (without matrix). (b) Illustration of cracks that appear within the laminate in different cycles of operation. Due to specific design of the woven types of composites, the locations where the warps pass over the weft are sites of stress concentration from where initial surface cracks start.

The emitted waves are detected by a wide-band piezoelectric sensor and converted to an electrical signal. The AE sensor, a $WS\alpha$ model manufactured by Physical Acoustic Corporation, is a wide band AE sensor that has a frequency range of 100-900 kHz. The sensor is in 19.02 mm diameter with a stainless steel body and a ceramic face end. The temperature stability of the sensor is in the range of $-65^\circ C$ to $175^\circ C$. It is acoustically coupled to the specimen using a gel-type ultrasonic couplant and is firmly attached to the specimen. The received signals are amplified with 40 dB pre-amplification. The threshold level on AE counts is set to 45 dB and the Peak Definition
Time (PDT), Hit Definition Time (HDT) and Hit Lockout Time (HLT) are set to 50, 200, 300, respectively. Post-processing is performed on the measured data before performing statistical analysis. For example, AE data with average frequency—the ratio of the counts over duration—above 450 kHz are eliminated from the analysis. Signals of zero energy are also filtered out according to the filtering rules on AE signals measured from composite; See [36, 37]. The extracted AE features are counts, amplitudes, energy and average frequency. The counts are defined as the number of times that the AE amplitudes exceeds a preset level (threshold) and the energy is derived via integration of the rectified voltage signal over the duration of the AE signal and is computed by AEwin software. The AE energy emanates from the elastic energy release and the energy release due to fracturing processes that occur during the cyclic loading [38-40].

4.3.2 Behavior of the AE Signatures Associated with Damage

Table 4.1 summarizes the time-to-failure results of six fully-reverse bending fatigue tests performed at different frequencies (7, 10, and 15 Hz) and displacement amplitudes (38.1, 41.91 and 43.18 mm).

Table 4.1. Experimental conditions of the performed experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Displacement amplitude (mm)</th>
<th>Frequency (Hz)</th>
<th>Time to failure (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38.1</td>
<td>7</td>
<td>1225</td>
</tr>
<tr>
<td>2</td>
<td>38.1</td>
<td>15</td>
<td>394</td>
</tr>
<tr>
<td>3</td>
<td>41.91</td>
<td>7</td>
<td>497</td>
</tr>
<tr>
<td>4</td>
<td>41.91</td>
<td>10</td>
<td>240</td>
</tr>
<tr>
<td>5</td>
<td>43.18</td>
<td>7</td>
<td>348</td>
</tr>
<tr>
<td>6</td>
<td>43.18</td>
<td>15</td>
<td>125</td>
</tr>
</tbody>
</table>

The results show that the higher the displacement amplitude and frequency, the shorter is fatigue life. Figure 4.2 shows the evolution of the acoustic emission descriptors including energy (Figure 4.2 (a)), counts (Figure 4.2 (b)) in a typical experiment with a fresh specimen subjected to
cyclic bending until final fracture take place. The cumulative form of the AE energy (Figure 4.2 (a)), and counts (Figure 4.2 (b)) exhibit a persistent three-stage trend in all experiments. These stages are identified on cumulative energy plot (Figure 4.2 (a) and (b)) and labeled as Stage I, II and III. Similar three-stage trend in damage evolution in composites is reported elsewhere [34, 39, 41-46].

Figure 4.2 (a) Cumulative acoustic emission energy (left axis in log scale) and AE energy (right axis) in a typical fully reversed bending fatigue experiment. The displacement amplitude is 43.18 mm and the frequency is 7 Hz. (b) Cumulative acoustic emission counts (left axis in log-scale) and AE counts (right axis). A three-stage behavior can be identified from the all of the AE descriptors as a result of the different damage mechanism inside the laminated due to cyclic loading. (c) Average frequency of the AE signals from which the transition from Stage II and III is identifiable. The average frequency increases significantly due to the fiber breakage damage mode.

This type of trend is reproducible and observed in different measures of degradation such as acoustic emission energy [34], temperature profile or dissipated heat [34] and loss in modulus of elasticity [47]. This behavior is related to damage evolution trend of the composite materials and the appearance of damage mechanisms in a chronological order. The idealized damage profile in
composites can be seen in the studies by Toubal et al. [47] and Mao et al. [41]. In the first stage, matrix cracking occurs at weak points of the material. In the second stage, debonding and fiber matrix delamination take place. Matrix cracking is also continuing in the second stage. In addition to the previous damage mechanisms, the final stage of operation is accompanied with fiber breakage that continues until final failure [33, 34]. The final stage of the operation manifests itself in the form of a sudden increase in the AE energy and counts. The transition from Stage II to III can be identified from the average frequency of the AE signals as it is depicted in Figure 4.2 (c). AE signals measured from glass/epoxy laminates under cyclic loading exhibit an average frequency up to $100 \pm 10$ kHz in the first and second stages of their life. This average frequency is indicative of damage mechanisms such as matrix cracking formation and coalescence as well as debonding. The average frequency will increases significantly due to damage modes such as fiber breakage. Two items are worth pointing out: firstly, that the fiber breakage may also be present in the earlier stages of the operation. However, the last stage of the fatigue life is where significant fiber breakage occurs. Secondly, one may not be able to define a very distinct line for the transition from one stage to another specifically from Stage I to II. Stage I ends after few cycles of operation as a result of the rapid damage accumulation and is of a duration almost 10-20 percent of the total life [34, 41, 48].

4.3.3 SEM of the Fatigue Fracture Surface

As the stress increases, the micro-fracturing process start to nucleate from the available faults and eventually causes fracture [49-51]. The damage localization is a process in which cracks do not coalesce but are in close neighbored [52]. Figure 4.3 shows SEM images of the localization of the defects on the surface of the Glass/Epoxy at various stages, from the virgin specimen (Figure 4.3 (a)) until the final failure (Figure 4.3 (e)). The first surface cracks that can be captured using
SEM are shown in Figure 4.3 (b). After more cycles of loading, the surface cracks tend to coalesce and the damage starts to localize around the initial flaws (Stage II). This can be observed from Figure 4.3 (c) where two parallel cracks are about to coalesce. Eventually after more cycles are passed, as shown in Figure 4.3 (d), cracks are connected and increase the severity of the damage (end of the Stage II). Such events result in the final failure as in Figure 4.3 (e) (Stage III). It is worth pointing out that subsurface damage and defects may exist but are not captured by SEM analysis.

Figure 4.3. Evolution of damage from the beginning of the test (a) until the failure time (e). (a) Intact surface of the specimen (Stage I). (b) Surface cracks on the points where warps and wefts pass over each other (End of the Stage I and beginning of the Stage II) (c) coalescence of the cracks (d) crack localization (e) multiple local cracks leads to final failure (Stage III).

4.4 Statistical Analysis of AE Features

4.4.1 Estimation of the PDF of the AE Descriptors using Power-Law Distribution

The histogram of the energy of the acoustic emission in a typical fatigue experiment is right skewed with a long tail to the right [2] revealing that high energy bursts are less probable than more moderate ones. In a typical fatigue experiment, the initial cycles of the experiment yield low
energy AE signals. As the number of cycles increases, higher energy signals are recorded due to the accumulation of several damage mechanisms inside the laminate.

The form of the energy distribution can be described by the power-law distribution. A quantity is said to follow a power law if it can be obtained from a probability distribution described by equation 1.

\[ p(x) = cx^{-\alpha} \]  

(1)

where \( c \) is a constant and the exponent \( \alpha \) is the so-called scaling parameter of the distribution [2, 53]. The exponent can be estimated using the linear bins, logarithmic bins [54], by employing the cumulative distribution function (CDF) [55] or by applying maximum likelihood estimation procedure [53]. For a comparative study of these methods the reader is referred to refs [53, 56]. The maximum likelihood estimation (MLE) method in particular, provides an accurate estimation of the power-law exponent [53, 56-58]. In this paper, we estimate the power law exponent of the AE energy and counts based on the MLE procedure introduced by Clauset et al. [53].

4.4.2 Behavior of the PDFs of AE Energy and Counts

Statistical analysis is performed on the AE energy and counts associated with signals of six fatigue experiments summarized in Table 4.1. Typical behavior of the AE features (count and energy) in fatigue experiments are shown in Figures 4.2 (a) and (b). The probability density functions (PDF) of the AE energy and counts are plotted in Figures 4.4 and 4.5, respectively. For each experiment a power law is fitted to the distribution. The exponents of the energy distribution, \( P(E) \sim E^\alpha \), and counts distribution, \( P(C) \sim C^{-\alpha} \), are computed using the MLE method [53]. The insets shown in the Figures 4.4 and 4.5 are boxplots for each estimated exponent \( \alpha \) and its range. The central red marks represent median, and the margins of the box show the 25th and 75th percentile variation. Each side of the whiskers corresponds to the largest data points that are
not evaluated as outliers. It is observed that the AE energy and count follow the scaling function of the form \( f(E) \sim E^{-1.8} \) and \( f(C) \sim C^{-1.86} \). The ranges of the energy exponent is \( \alpha = 1.8 \pm 0.05 \) (with the mean of \( \alpha = 1.8 \) and median of \( \alpha = 1.79 \)) and that for the count distribution is \( \alpha = 1.86 \pm 0.05 \) (with the mean of \( \alpha = 1.86 \) and the median of \( \alpha = 1.84 \)).

Figure 4.4. PDF of AE energy data versus acoustic emission energy of the bending fatigue tests. The low energy regime decays as a power law with exponent, \( \alpha = 1.8 \pm 0.05 \). The inset is the boxplot of each estimated exponent \( \alpha \). The figure is in double-log scale and the logs are in base 10.

Figure 4.5. PDF of AE counts data versus acoustic emission counts of the bending fatigue tests. The low counts regime decays as a power law with exponent, \( \alpha = 1.86 \pm 0.05 \). The inset is the boxplot of each estimated exponent \( \alpha \). The figure is in double-log scale and the logs are in base 10.
The evolution of the PDF of acoustic emission energy (Figure 4.4) and counts (Figure 4.5) from the beginning of the fatigue tests until fracture demonstrates a power-law at low energies (counts) with a deviation from power-law in high energies (counts). The presence of this change in the PDF of the released elastic energy as well as in the AE counts of the laminates is indicative of a stage in the degradation where several damage modes are present and that the statistics of the AE energy release tend to change due to the greater number of the AE events associated with the higher energies and counts. The occurrence of such regimes associated with fracture energy under different displacement amplitudes has also been reported by Picallo et al. [10].

There are very few studies that concentrate on the investigation of the fatigue failure pertinent to statistical analysis of the AE features. One such work is a recent paper of Dunand-Châtellet et al. [59] that also employs the MLE to estimate the power law distribution in AE energy release during the fatigue loading of the NiTi shape memory alloy. In their work [59], the exponent of $\alpha = 1.8$ is reported for the “stable state” of the material where dissipation of the energy is low. Experiments on polyurethane foams conducted by Deschanel et al. [26] reveal that AE energy in creep experiments can be described by power law of the exponent $\alpha = 1.76 \pm 0.1$, which is estimated by a linear fit to the distribution on a log-log scale. The AE energy data in [26] is logarithmically binned.

As depicted in Figures 4.2 (a) and (b), the low energy (or counts) regime is attributed to the stage where the state of the damage in the specimen is limited to the initiation of matrix cracking and matrix/fiber debonding and less severe damage [34, 44]. The higher energy (or counts) regime is caused by more severe cracking, delamination and fiber breakage [34]. These results demonstrate that, under the conditions tested, in the low-and high-energy (counts) regimes, the probability distribution is not dependent upon the displacement amplitude or the frequency of the
The appearance of a scale-free behavior of the AE energy is a sign of the so-called self-similar behavior. The same type of rupture with the scaling behavior in energy is also reported in the fracture of the rock samples under increasing stresses [25, 60, 61].

Several damage modes exist in the failure of the composite laminates. During the cycles that the severity of this damage mode are not appreciable, —that is, the stage where the integrity of the specimens are not changed significantly from their virgin condition— a similar power-law is observed for all of the specimens independent of the operational parameters. This implies that the acoustic energy release behavior is statistically similar for specimens under different loading conditions. The deviation from power-law is observed, however, once the typical damage modes of the laminate intensify and interact. The identification of the power-law in the AE energy release (or counts) and its divergence at the point where damage density becomes appreciable is indicative of the fact that fatigue rupture of the Glass/Epoxy laminates and their AE energy release (counts) is independent of various operational conditions. As suggested by an anonymous reviewer, the size of the specimens and boundary conditions may affect the behavior of the AE features. Those were not included in our experimental variables; Indeed, investigation of the size effect and boundary conditions would lead to more valuable insight on the nature of acoustic emissions regimes.

4.4.3 Amplitude Distribution (Cumulative Form)

Figure 4.6 depicts the cumulative form of amplitude distribution of the six experiments presented in Table 4.1 in the form of the whisker-and-box plot. The abscissa is the amplitude in Volt and the ordinate represents the number of AE hits that exceed that amplitude. In this plot, each box contains the results of the six experiments. For instance, the boxplot related to the $45 \, dB$ represent the number of AE events of six fatigue experiments that have an amplitude larger than $45 \, dB$. The center-line of the boxes shows the median and the margins of the box depict the 25%
and 75% percentiles. It is observed that the number of AE event, \( N(A) \), decreases as the AE amplitudes increases.

In Figure 4.6, the amplitudes within the range of [40-80 dB] show an approximately linear trend. The range for the amplitudes in the interval of the [45-65 dB] is smaller than that of the rest of the amplitudes, and this interval belong to the cycles of operation where damage is not significant.

The number of AE events \( N(V) \) with amplitudes greater than threshold amplitude follows a linear relationship when plotted in the double-log scale as in equation 2.

\[
\log N(V) = -\alpha \log V + b
\]  

(2)

where \( V \) is the amplitude data in Volt , \( \alpha \) is slope of the linear fit in the log-log scale. In the linear scale, equation 2 transforms into a power-law relation in the form of equation 3.

\[
N(V) = aV^{-\alpha}
\]  

(3)

Figure 4.6. Box plot of the AE amplitude distribution data for the six fatigue experiments. The central red marks represent median, the margins of the box show the 25th and 75th percentiles. Each side of the whiskers correspond to the largest data points that are not evaluated as outliers. The outliers are plotted by the plus signs. A deviation in the power law behavior is observed in small amplitudes (below 45 dB) and large amplitudes (above 85 dB). Such a deviation in the two extremes of the amplitudes, also reported in [3, 62], is due to the lower and upper cutoff limit of the AE recording apparatus.
Figure 4.7 shows a linear fit to the median of each box in Figure 4.6. The fit has the slope of $\alpha = 1.94$, which is similar to the slope reported by Petri [62] in experiments involving cylindrical specimens of synthetic plaster (Ancorfix 709) in a uniaxial elastic stress. Two linear fits with the slopes of $\alpha = 2 \pm 0.1$ are also obtained in tests with volcanic rocks [63] and with crystalline materials [64]. In all of these three references [62-64], the authors reported a scaling law of the form $N(V) \sim V^{-\alpha}$ with $\alpha = 2$ in the amplitude distribution of the AEs. The power-law exponents in the cumulative form of amplitude distribution of the AE signals emerging from the fracture of different materials appears to be a constant value and indicative of self-similarity in the fracture of the brittle materials. We now explore the relation between the AE amplitudes and AE energies. This was suggested by an anonymous reviewer.

To obtain such a relation, the average energy of AE events of a particular amplitude, e.g. A (dB), is computed for all of the experiments and shown as a function of amplitudes in double-log form. The AE amplitudes are converted from dB to Volt using the relation $V = 10^{\frac{A}{20}} \times 10^{-6}$. This method is also employed by Vives et al. [65] to obtain the exponent characterizing the statistical dependence of AE amplitude with AE duration.

Figure 4.7. The median of the each box in Figure 4.6 versus amplitudes shows a linear relation in double-log- scale. A linear fit on the medians of the box plots versus amplitude is applied. The amplitudes are transformed from dB unit to volt (V) using the relation $V = 10^{\frac{A}{20}} \times 10^{-6}$ where $A$ is the AE amplitudes in dB. The linear fit has the slope of 1.94.
Figure 4.8 demonstrate the boxplot of the AE average energies of amplitude $A$ associated with the six experiments in Table 4.1 plotted versus the amplitudes in double-log form. The abscissa ranges from 40 to 100 $dB$ converted the Volt.

The inset of the Figure 4.8 shows the median of each box in blue circles in log-log form. A line are fit to the median values in a least square sense is shown. It has a slope of 1.2 and a y-intercept of 4.7.

If the statistical distributions of AE features such as amplitude and energy are described by a probability density functions such as $p(E)\sim E^{-\varepsilon}$, and $p(A)\sim A^{-\alpha}$, then the energy and amplitude are related statistically through the relation, $E\sim A^z$ and the relation, $\alpha - 1 = z (\varepsilon - 1)$ holds for the exponent [65, 66]. According to this relation, given $\alpha = 1.94$ and $\varepsilon = 1.79$, one obtains the $z = 1.19$ which is very close to the slope, $z = 1.2$ obtained in the inset of the Figure 4.8.

![Figure 4.8](image_url)

Figure 4.8. Statistical dependence of the AE energy with AE amplitude. Each box contains the average energy of the measured AE signals at each amplitude ($E|A$) pertinent to six experiments. Both axes of the figure and its inset represent the logarithm of the average AE energy of amplitude $A(V)$ and AE amplitude in base 10.
4.5 Summary and Conclusions

In this research, we examined acoustic emission patterns of the fatigue failure involving cyclic bending tests of the Glass/Epoxy laminates. The results are corroborated by SEM analysis. The PDF of the acoustic emission signatures including energy, counts show a power law in multiple decades with a cross-over as the severity of the damage modes increase and failure is approaching. It is observed that the AE energy follows the scaling function of the form \( f(E) \sim E^{-1.8} \) and the range of \( \alpha = 1.8 \pm 0.05 \) is obtained for the exponent of the energy distribution in close agreement with [59]. Under the condition tested, the AE energy release and AE counts exhibit a universality feature wherein the scaling function and the power laws do not depend on the specimens or the operational conditions. However, material dependency on the values of the exponents is expected. It is demonstrated that the cumulative amplitude distribution of the AE signal can be described by a power law of the form \( N(A) \sim A^{-\alpha} \) with the exponent of \( \alpha = 1.94 \). This is in agreement with several studies that we are aware of such as [62-64].

Such a scaling law seems to be independent from the operating conditions and suggest universality in the statistics of the AE signatures. The reason behind this universality is the consistent damage forming mechanisms and the fact that there exists a critical damage level beyond which the material fails. There are many factors that affect the values of the acoustic emission measurements such as location of the sensors, measurement system parameters, specimen size, environmental parameters, and material properties. However, the present studies, along with cited literatures, reveal that there exists a universal feature in the statistics of the AE features. Hence, monitoring a statistical feature such as the power exponent or a scaling function instead of relying solely on the sensor output may improve the performance of future structural health monitoring schemes and much worth further studies.
4.6 References


Chapter 5. Entropic Fatigue Damage Detection and Health Monitoring: Application to Composite Materials

In this chapter, we report a damage detection and health monitoring method based on the Shannon information entropy. The method relies on the calculation of the cumulative entropy from the acoustic emission counts measured from composite specimens subjected to the cyclic bending load. The cumulative entropy demonstrates a persistent trend of nonlinear damage evolution typically observed in the experimental measures of the damage in composite materials—e.g. dissipated heat energy and loss in elastic modulus.

5.1 Introduction

Structures and mechanical components subjected to cyclic loading undergo gradual degradation that ages the component and eventually results in fatigue failure. Much progress has been made on the development of methodologies for predicting the number of cycles to failure [1-4] as well as the theoretical modeling of the damage in solids [5-12]. Yet, to date a reliable procedure for assessment of cumulative damage remains elusive. To design a structural health monitoring system (SHM) for a specific application, it is crucial to first identify an appropriate feature in the system’s response that can properly assess the level of the deteriorations. This aim cannot be accomplished successfully without appropriate identification of the damage mechanisms involved. To this end, various structural health monitoring (SHM) and non-destructive evaluation (NDE) methods have been proposed. Some of the available methods study the response of the material using vibration analysis [13-20] and magnetic Barkhausen noise analysis [21-24]. Still others base their assessment on the changes in material properties such as hardness [25, 26], electrical resistance [27-29] variations of stiffness [30, 31] and thermodynamic entropy [32-34]. Relevant to composite materials, recent literature provides significant progress in evaluation of damage using infrared thermography [35-44] and acoustic emissions (AE) [35, 36, 45-48].
Thanks to the progress made in development of the sophisticated AE hardware setups, acoustic emission signals can be measured now in various environmental conditions. The benefits of utilizing AE is not limited to the range and ease of applicability, there are damage mechanisms that can be captured solely utilizing AE. For instance, in particular application of the fiber reinforced laminates in addition to damage formation and propagation zones—that can be captured by both thermography and AE techniques—AE signals are also emitted from dissipation processes where fiber/matrix debonding occurs [49, 50].

The objective of this paper is to investigate the utilization of diagnosis features that depend on the distribution of the AE measurements instead of their values that can improve the generalization properties of a health monitoring system. For this purpose, we employ information entropy as a distributional feature that depends on the probability distribution of the measurements rather than each specific value. Information entropies have been used in diverse disciplines, particularly in signal and image processing. For instance, Coifman et al. [51] used entropic measures as cost functions in signal and image compression. Kapur et al. [52], Sahoo et al. [53] and Albuquerque et al. [54] employed the information entropy for image thresholding, and Sabuncu [55] utilized it for image registration. In dealing with signal processing of the mechanical and structural systems, Overbey et al. [56] employed the transfer entropy as a feature for damage identification. Yan et al. [57, 58] employed permutation entropy [57] and approximate entropy [58] for fault diagnosis of the rotary machines. In these cited literatures, the information entropies, are used for determining the order—as opposed to scatteredness— of the time-series* [59] of physical measurements—e.g. a signal or an image—to quantify their information content. Entropy

* Time-series is defined as a time-oriented sequence of data-points of a random variable to be studied.
can be interpreted from different views such as an uncertainty in a random variable, as a measure of gaining information about a random variable, and as a measure of dispersion in a probability distribution of a random variable [55, 60].

This study incorporates information entropy—in particular, the Shannon definition of the information entropy [61]—of the acoustic emission cumulative counts as a damage index that characterizes the degradation evolution of the glass/epoxy laminates. The premise of this research is that fatigue damage in composite laminates is a form of disorder which manifests itself in the deteriorations in the features of the acoustic emission signals and can be quantified employing information entropy. We intend to show that the information entropy of the AE features reveals the damage evolution trend of the laminate. The outline of this chapter is as follows: A description of the elements of the proposed entropic damage detection technique is presented in Section 5.2 which also includes a brief review of the damage indices related to composite materials. Section 5.3 introduces the material and experimental apparatus. Section 5.4 presents the results of the fully reversed fatigue experiments on woven glass/epoxy laminates and discuss the performance of the defined entropic index.

5.2 Elements of the Damage Detection Scheme

5.2.1 Entropy Estimation

The key step to calculate the entropy is the estimation of the probability distribution of the observations. The probability distribution provides knowledge about the states of the measured time-series. Assume that a system composed of a set of finite states, \( \omega_1, \ldots, \omega_n \), has a probability distribution of \( P(p_i) \). The information entropy, \( S \),—referred as the Shannon’s entropy in recognition of Claude E. Shannon’s work in 1948— of such a distribution, \( P(p_i) \), is defined as follows [61-63].
\[ S = \sum_{i=1}^{n} p_i \log \left( \frac{1}{p_i} \right) = -\sum_{i=1}^{n} p_i \log(p_i) \]  \hspace{1cm} (1)

where \(0 \log(\infty) = 0\), \(p_i\) is the probability of each state \(\omega_i\).

The base of the logarithm specifies the units. For instance, for base 2 and natural base \(e\), the Shannon entropy is measured in \textit{bits} and \textit{nats}, respectively. In the equation 1, the \(\log \left( \frac{1}{p_i} \right)\) is interpreted as the amount of uncertainty associated with the corresponding outcome or the information obtained by observing that outcome. One can conclude that the Shannon definition of entropy provides a statistical average of information or uncertainty. The desirable properties of the Shannon entropy are: it is a concave function of \(p_i\) and has the additive property. The entropy is maximum when the probabilities of occurrences of all of the events are equiprobable. It is also not dependent on the values of the random variable but is dependent on its distribution.

Equation 1 can be generalized to continuous systems defined by a continuous probability distribution. One can obtain the Shannon entropy of a continuous random variable, \(X\), as \(S(X) = -\int p_X(X) \log(p_X(X)) dX\), where \(p_X(X)\) is the probability distribution of the continuous random variable \(X\) [60]. Given the probability density function (PDF) of the system under investigation, the entropy is formulated as in equation 2 as follows [64].

\[ S = -\int PDF(x) \log(PDF(x)) dx \]  \hspace{1cm} (2)

5.2.2 Histogram Estimation

The first step in determining, \(S\), is to estimate the probability distribution of the given random variable by computing the histogram of the observations. The histogram of a dataset can be estimated by employing several methods including linear, logarithmic binning of the data or by using the cumulative distribution function (CDF) of the data. In the linear binning approach—which is the simplest method—the observed data is stacked in bins of linear width. The number of bins is arbitrary. But, there are methods to obtain a somewhat optimized number of bins such
as Doane’s formula [65], Scotts’ normal reference rule [66], and Freedman-Diaconis rule [67]. In logarithmic method, bins have constant logarithmic width and the number of bins in larger values of the data is reduced. This is a desirable property in most applications; however, it has the disadvantage that the number of data in each bin is also dependent on the bin width [68]. In CDF method, employed in this paper, the estimation procedure does not need binning. A brief description of the procedure follows.

Let $X$ represent the variate whose range is denoted by $R_X$. Let $p_i$ designate a real number that ranges between 0 and 1 representing the probability of the variate. The distribution function $F_X$ or cumulative distribution function (CDF) pertaining to the variate $X$ is defined as following [69].

$$F(x) = \Pr[X \leq x] = p_i, \quad x \in R_X, p_i \in R_X^{p_i}$$

(3)

The $F(x)$ is interpreted as the probability that the variate $X$ attains values smaller than or equal to $x$. It is a non-decreasing function that attains 1 at the maximum value of the variate $x$ [69]. Let $x_i, i = 1, ..., n$ be an $n$-dimensional subset of $X$. For computing the CDF, the observations, $x_i$, are sorted in an ascending order and then the CDF is estimated as $\frac{i}{n}$ which is the so-called Kaplan-Meier estimate [68, 70-72]. The histogram is obtained from the computed empirical CDF whose heights are calculated from the increases in the empirical CDF and once normalized to the heights of the histogram, it represents the probability domain of the corresponding variable. Two Matlab functions of ecdf and ecdfhist are used to for computing the CDF and the probability domain. Once the probability domain is computed, one is able to estimate the entropy of the given data.

5.2.3 Entropic Damage Index

Equation 4 defines the damage index based on the cumulative Shannon entropy of the AE cumulative counts. In this equation, $S(n)$ represents the cumulative Shannon entropy of the AE
cumulative counts at the \( n^{th} \) cycle of the operation. \( S_0 \) and \( S_f \) are the corresponding values at the initial and final instant of operation pertaining to the pristine laminate and the onset of fracture, respectively. In defining the entropic damage index, equation 4, the acoustic emission counts are regarded as the signatures of the micro-fracturing processes that occur in the laminate during the fatigue loading. We treat the acoustic emissions occurring within the straining cycles of the specimens as a random event and define our variate as the acoustic emission cumulative counts.

\[
D(n) = \frac{S(n) - S_0}{S_f - S_0}
\]

A number of damage indices pertaining to fatigue failure of the composite materials are summarized in Table 5.1. Damage indices shown in equations 5-7 are rooted in experimental development and equations 8 and 9 are analytical. The definition of the damage index in equation 4 is similar to three damage indices introduced by Giancane et al. [73], Mao et al. [74] and Azouaoui et al. [75, 76] that are defined based on the evolution of the dissipated heat, loss in modules of elasticity and degradation of the bending stiffness, respectively.

Mao and Mahadevan [74] introduced a damage index—equation 5 obtained by modification of the Lemaitre damage index [77]—where the parameter \( D \) is the accumulated fatigue damage, \( E_0 \) is the elastic modulus of the material in its pristine condition, \( E \) is the elastic modulus in the damaged configuration and \( E_f \) is the elastic modulus when the specimen fails.

The damage index varies in the interval of [0 to 1]. Giancane et al. [73] make use of the dissipated energy during the fatigue loading of the laminates to define a damage index as given in equation 6, where \( H \) represents the dissipated energy per cycle and per unit of length, and \( H_0 \) and \( H_f \) are the initial and final condition, respectively. The model uses the dissipated energy to characterize the three-stages trend of the damage progression in composites.
Azouaoui et al. [75, 76] studied the variations of the bending stiffness to quantify the accumulation of the fatigue damage induced by impact cyclic loading and to characterize the three stages in the life of the laminates. equation 7 describes their damage parameter where $R_0$ and $R_f$ represent the initial and final stiffness and $R_i$ is the bending stiffness of the damaged material at the time instant of the $t = t_i$.

Table. 5.1. Experimental damage variables and analytical models for damage evolution in composites

<table>
<thead>
<tr>
<th>Equation</th>
<th>Damage indicators by:</th>
<th>Definition</th>
<th>Physical parameter to define damage indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation 5</td>
<td>Mao et al. [74]</td>
<td>$D = \frac{E_0 - E}{E_0 - E_f}$</td>
<td>Modulus of elasticity</td>
</tr>
<tr>
<td>Equation 6</td>
<td>Giancane et al. [73]</td>
<td>$D = \frac{H - H_0}{H_f - H_0}$</td>
<td>Dissipated thermal energy</td>
</tr>
<tr>
<td>Equation 7</td>
<td>Azouaoui et al. [75, 76]</td>
<td>$D = \frac{R_0 - R_i}{R_0 - R_f}$</td>
<td>Bending stiffness</td>
</tr>
<tr>
<td>Equation 8</td>
<td>Mao et al. [74]</td>
<td>$D = q \left( \frac{n}{N} \right)^{m_1} + (1 - q) \left( \frac{n}{N} \right)^{m_2}$</td>
<td>-</td>
</tr>
<tr>
<td>Equation 9</td>
<td>Wu. et al. [78]</td>
<td>$D = 1 - \left( 1 - \left( \frac{n}{N} \right)^{B/A} \right)$</td>
<td>-</td>
</tr>
</tbody>
</table>

The elements of the damage detection scheme are shown in the Figure 5.1. In brief, after AE signal acquisition, the histogram of the AE cumulative counts is estimated using the Kaplan-Meier cumulative density function (CDF) [72]. The CDF is estimated without assuming any prior distribution for the AE cumulative counts. Then, the cumulative Shannon entropy of the AE cumulative counts along with its derivatives are computed.

5.3 Materials, Experimental Apparatus and Procedure

The type of composites used in this work is glass/epoxy (G10/FR4)—an unbalanced woven fabric with plain weave-and-aligned configuration stacked in fifteen layers within the thickness of 3 mm.
The specimens are prepared with on-axis stacking sequences, and manufactured for use in reverse-bending fatigue tests with a similar configuration reported in [35, 48].

![Diagram of the proposed health monitoring system](Image)

Figure 5.1 The procedure for the proposed health monitoring system.

The laminates are clamped at one end while the other end is oscillated with a specified amplitude and frequency. The detailed depiction of the bending fatigue apparatus is presented in [35]. Table 5.2 summarizes the mechanical properties of the specimens.

Table 5.2 mechanical properties of the specimens.

<table>
<thead>
<tr>
<th>Crosswise elastic modulus (MPa)</th>
<th>Lengthwise elastic modulus (MPa)</th>
<th>Crosswise flexural strength (MPa)</th>
<th>Lengthwise flexural strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.1</td>
<td>18.6</td>
<td>310</td>
<td>379</td>
</tr>
</tbody>
</table>

A PCI-2—a two-channel AE system which samples up to a rate of 10 MHz— is utilized to measure the acoustic emissions from the specimen during the entire test. A wide-band acoustic emission sensor measures the emitted waves and converts them to an electrical signal. The AE sensor is 19.02 mm in diameter and has a frequency range of 100-900 kHz. A gel-type ultrasonic couplant is used to acoustically couple the sensor to the specimen. The sensor is firmly connected to the specimen during the fatigue tests. A pre-amplification of 40 dB is applied to the received
signals. The threshold level on AE counts is set to 45 dB. The Peak Definition Time (PDT), Hit Definition Time (HDT) and Hit Lockout Time (HLT) are set to 50, 200 and 300, respectively. AE data with average frequency—the ratio of the counts over duration—above 450 kHz are eliminated from the analysis. Signals of zero energy are also eliminated. The AE counts are defined as the number of times that the AE amplitudes go beyond the threshold level. Figure 5.2 (a) demonstrates a typical acoustic emission signal and the threshold level. Each time the AE amplitude reaches the threshold level, a count is registered. Figure 5.2 (b) depicts the AE counts in a typical fatigue experiment from the beginning until the failure of the specimen where it breaks. Figure 5.2 (b) shows that the stages in the lifespan of the laminate can be distinguished from the acoustic.

![Figure 5.2 (a)](image)

Figure 5.2 (a) A typical acoustic emission signal. The AE counts and the threshold level is defined schematically. (b) The AE counts for a typical fatigue experiment under the displacement amplitude of 43.18 mm and frequency of 7 Hz.

As an alternative method to acoustic emission, we also utilize infrared thermography to characterize the degradation of the laminate and to corroborate the trend of the thermal and acoustic response of the laminates as they degrade. The temperature evolution was captured using an infra-red (IR) camera, Mikron 7500, with a temperature range of 0–500 °C, 320x240 pixel resolution and a sensitivity/Noise Equivalent Temperature Difference (NETD) 0.08°C at 30°C.
5.4 Results

Figure 5.3 shows the cumulative Shannon entropy and cumulative AE counts of a typical fully reversed bending experiment on a glass/epoxy laminate. The trend of the cumulative Shannon entropy, Figure 5.3 (a), reveals the nonlinear trend of the damage evolution in composites. Comparing the cumulative acoustic emission counts, Figure 5.3 (a) (right-axis), with cumulative Shannon entropy, Figure 5.3 (a) (left-axis), over the life of the laminate, it is observed that the entropy distinguishes the non-linear three stages trend of the damage evolution in the life of the laminate better than the cumulative counts itself.

![Graph](image)

Figure 5.3 (a) Acoustic emission cumulative Shannon entropy (left axis), acoustic emission cumulative counts (right axis). (b) The surface temperature of the same experiment. The cumulative entropy and the temperature profile show the typical trend of the damage formation in composites.

The cumulative entropy enables us to study how the emission regime varies throughout the experiment. This immediately suggests particular attention should also be allocated to how the emissions are changed with respects to the previous signals. Such information cannot be extracted from magnitudes of the AE features, for instance counts and energy, and from simply studying the accumulated trend of the AE features or the number of acoustic events. However, the accumulated
Entropy is observed to be capable of distinguishing such transitions in the AE regimes. To ensure that the trend observed in the accumulation of the entropy manifests the damage accumulation, we probe into another mechanism of dissipation of the material—that is, the thermal response of the laminates—to investigate if such a trend observed in accumulation of the information entropy can also be identified simultaneously in other mechanism of dissipation e.g. thermal energy. During the cyclic loading of the laminate a fraction of the mechanical work applied on the specimen is dissipated in the form of thermal energy which gives rise to the temperature of the laminate [79-81] and is related to the damage energy [37, 82]. Figure 5.3 (b) depicts the surface temperature profile of the laminate during the cyclic loading—corresponding to the same test—obtained utilizing infrared thermography.

One is able to observe that the evolution trend of temperature and cumulative entropy are indeed similar in trend over the course of the fatigue loading. The trend observed in the cumulative Shannon entropy and in the temperature profile in Figure 5.3 (a) —which is the general form of the damage evolution—is reproducible. The reproducibility is tested under different experimental conditions including various displacement amplitudes or frequencies. Two sample experiments are shown in Figures 5.4 (a) and (b) where the cumulative Shannon entropy and the corresponding damage index, equation 4, are demonstrated. To evaluate the damage index defined based on cumulative Shannon entropy in equation 4, we also employ two nonlinear analytical damage models proposed by Mao et al. (equation 8) [74] and Wu et al. (equation 9) [78] that describe the damage progression trend in composites. In equation 8, \( q, m_1 \) and \( m_2 \) are material constants; \( n \) is the number of applied loading cycles, and \( N \) is the fatigue life at a specified applied load level. This model can appropriately represent the three-stages trend of the damage evolution in the composite materials. Equation 9 is based on stiffness degradation of the laminates where \( N \) is the
fatigue life and $A$ and $B$ are the model parameters that can be obtained experimentally. The fatigue
damage index is zero when $n = 0$ and tends to its limit value ($D = 1$) when the $n = N$.

Figure 5.4 (a) The cumulative entropy (Left axis) and the damage parameter (Right axis), versus the time. The two tests are performed under the displacement amplitude of 41.91 mm and 38.1 mm, respectively. The frequency of applying the loading is 7 Hz.

Figure 5.5 (a-c) shows the damage index versus the normalized number of cycles computed by both the analytical method and the entropic indicator defined in equation 4. The parameters for these two models are computed for the two experiments and are shown in Figures 5.5 (a) and (b) using a nonlinear curve-fitting procedure in a least square sense*. The computed parameters of the Mao’s model, Figure 5.5 (a), are $q = 0.6633$, $m_1 = 0.6358$ and $m_2 = 16.3342$ for the experiment of the 38.1 mm displacement amplitude and those of the experiment with displacement amplitude of 41.91 mm are $q = 0.7969$, $m_1 = 0.5493$ and $m_2 = 20.9071$. The obtained

* The procedure in general form is that given input data, $x_{\text{input}}$, the observed data, $y_{\text{observed}}$ and the model, $F$, the following minimization problem is formulated that finds coefficients $x$ that solve the following problem:

$$\min_x \| F(x, x_{\text{input}}) - y_{\text{observed}} \|_2^2 = \min_x \sum_i F(x, x_{\text{input}}) - y_{\text{observed}})_i^2$$

For details of the used least square nonlinear minimization, please see :[83-84]
parameters for the Wu’s model, Figure 5.5 (b), are $A = 0.4098$ and $B = 0.4614$ for the experiment of the displacement amplitude of 38.1 mm and those of the experiment of displacement amplitude of the 41.91 mm are $A = 0.4949$ and $B = 0.3639$.

![Image](image_url)

Figure 5.5 Evaluation of the damage parameter by to analytical model by a) Mao et al. [74] and b) Wu et al. [78]. c) comparison of the experimental entropic damage parameter with two analytical model of the Mao et al. [74] and Wu et al. [78].

In Mao’s analytical model, the rapid damage accumulations during the initial cycles is modeled by the first term of the equation 8, $q \left( \frac{n}{N} \right)^{m_1}$, provided that $m_1 < 1$. The second term in
equation 8, models the rapid damage growth at the end of the fatigue life [74]. This model is incorporated by Giancane et al. [73] for evaluation of the experimental damage parameter based on heat dissipated energy defined in equation 6. Toubal et al. [85] employed this model to assess a damage parameter based on stiffness degradation and to predict the damage evolution.

Turning our attention to the Figure 5.5 (a) and (b), it can be realized that the damage values and the corresponding cumulative Shannon entropy at each number of cycle for the test of higher displacement amplitude, 41.91 mm, is higher than that of the test of lower amplitude displacement, 38.1 mm. In Figure 5.5c, the behavior of the damage index defined based on the cumulative Shannon entropy is plotted with the two analytical damage models. It is observed that the trend of the entropic damage index can be described very well with the analytical damage models. The Mao’s model [74] can capture more details of the changes that is typically observed in an experimental damage indices. For instance, in Figure 5.5 (c), at the normalized number of cycle \( n = 0.85 \), the Mao’s model can describe the entropic damage index more accurately than that of Wu’s [78]. The two terms defined in equation 8. enable the model to follow more complex trends compared to the equation 9.

5.4.1 Derivatives of the Cumulative Shannon Entropy

Damage indices are defined based on physical quantities that can represent the degradation evolution—e.g. heat dissipation, strain rate, stress, acoustic features. Consequently, the first derivative of the damage index can be interpreted as the rate of formation of the damage modes involved in degradation of a given material. The first derivative represents the rate of change in the corresponding metric utilized to study degradation of the material and is related to the rate of formation of the damage. For instance, Amiri and Khonsari [86, 87] have employed the evolution of the first derivative of the temperature as a function of time as a candidate for estimation of
remaining fatigue life. Their work is also extended to remaining fatigue life prediction of the welded joints by Williams et al. [2] where the evolution of the slope of the temperature, $R_\theta$, is reported as a promising quantity in determining the percentage of the consumed life of the welded steel specimens. Figure 5.6 (a) and (b) shows the cumulative Shannon entropy and its first and second derivatives. The rate of change of the cumulative entropy (Figure 5.6a), first derivative, shows a sharp decrease in its initial cycles.

![Figure 5.6](image)

Figure 5.6 (a) First and (b) Second derivative of the cumulative entropy versus time.

The variations in the first derivative remains confined until another sharp increase occurs in final cycles of operation before final fracture. The first derivative represents the growth rate of the damage. This trend can be explained physically considering the development of the damage mechanisms inside of the laminate in each cycle of the operation. As we march in time during the Stage I of the operation, rapid matrix cracking occurs. However, the matrix cracking rate decreases. The interval of a short duration and a decreasing rate observed in the evolution of the entropic damage index, Figure 5.6 (a) and (b) (left-axis), is due to this damage mode. The damage accumulates in each cycle of the operation. However, the rate of change of the damage formation
does not vary significantly (during Stage II) until the sharp increase (Figure 5.6 (a) right-axis) in cycles close to the final failure of the laminate in Stage III. The critical damage mechanisms in this stage of the life of the laminates are fiber breakages along with severe delamination that leads to final failure. This has an increasing growth rate.

The trends of the first and second derivatives of the cumulative Shannon entropy, or its corresponding damage parameter, are reproducible under several operational conditions as depicted in Figures 5.7 (a) and (b). Both of the $x$ and $y$ axes in Figures 5.7(a) and (b) are normalized with respect to the maximum corresponding value.

![Figures 5.7 (a) and (b)](attachment:image)

Figures 5.7 (a) The first and (b) second normalized derivatives of the cumulative entropy with respect to the normalized time. The experimental variables are summarized in the legend of the figures.

Similar behavior is observed in the first and the second derivatives of the temperature profile of the laminate and is depicted in the Figure 5.8(a) and (b). Such a trend in the rate of damage indices is observed in others methods of the damage characterization. For instance, Wu et al. [78], demonstrated the rate of the damage development—See Figure 5.9(a)—in Glass/HC9106-3, T300/QY8911 and AS4/PR500 laminates. Naderi and Khonsari [32] in an thermodynamic based
The approach employed the temperature profile to describe the damage evolution in AL 6061 specimens as depicted in Figure 5.9 (b). Pahutová et al. [88] report a similar trend in the creep rate of the AZ 91 matrix composites under different loading levels. Lamouroux et al. [89] also observed the similar trend in creep rate of the ceramic matrix composites where each stage in the strain rate is correlated to the corresponding damage mechanisms such as interfacial debonding and fiber breakage.

![Graph](image.png)

**Figure 5.8** (a) The first and (b) second normalized derivative of the surface temperature of the specimens with respective to the normalized failure time. The experimental variables are summarized in the legend of the figures.

### 5.4.2 Implications and Concluding Remarks

As a material degrades, the formation of the damage modes is reflected in its several physical characteristics. Since these deteriorations in the material properties are consequences of a common cause—i.e. formation and evolution of damage modes—, one is able to recognize similar trends in different responses of the material. In composites, as a heterogeneous material, damage evolution is composed of different stages which can be described as: scattered micro-cracks all over the laminate, coalescence of micro-cracks which are closely located, localization of the micro-cracks
and finally the crack growth. Several damage mechanisms are involved that are discussed in the paper.

Figure 5.9 (a) The rate of damage development of laminates [78], (b) The evolution of slope of the temperature where failure occurs at different load amplitudes in bending fatigue of Aluminum specimens [32]. Figures are shown with permission.

The formation of damage in the composites is associated with dissipative phenomena such as acoustic emissions. Throughout the life of the acoustic emission regimes undergoe changes as the level of the damage varies, new damage modes are formed and involved damage mechanisms coexist. Such changes are directly reflected in the features of the measured acoustic emission signals e.g. counts and its cumulative trend. As an immediate consequence of such regime changes, probability distribution of the AE features are affected. We can intuitively conclude that if one defines a proper feature capable of portraying such changes in the probability distribution of the AE characteristics, then valuable information can be disclosed regarding how the acoustic dissipation varies as material degrades.

We employed accumulated information entropy to characterize the damage evolution of the composite laminates. The cumulative entropy is observed to be an effective tool to identify the changes in the emissions regimes. This feature has the advantage that it is defined based on the distribution of the AE feature and not solely based on the values of the measurements.
To ascertain if the observed trend depicts the damage evolution of the laminates, the performance of this method is corroborated by an alternative damage characterizing technique which is infrared thermography. It was shown that, the behavior of this trend is similar to other signs of damage formation such as dissipated heat. Moreover, the performance of damage index is compared with two analytical models by Mao et al. [74] and Wu et al. [78] and it is shown that the behavior of the feature during the bending loading cycles can be described well with the two analytical models. Examination of the cumulative information entropy of the AE counts identifies the stage where incipient damage takes place and is sensitive to the development of the damage mechanisms involved in the failure of the woven laminate. More information regarding the states of the damage can be extracted from the derivatives of the cumulative Shannon entropy of the AE counts. Such indices can be used in practice, e.g. in monitoring softwares, as an “anomaly” detection feature that detects the irregularities in the integrity of the structure under monitoring.

Despite these motives to employ AE for SHM applications, however, the values of acoustic emission features may vary depending on the size of the specimens and boundary conditions. The microstructure and heat treatment also tend to affect the acoustic emissions. Further, the instrumentation setup, hardware adjustments and location of the sensors can affect the measurements and one may not be able to define a critical value for the features of the AE signals that holds for a variety of system variables and material characteristics. Consequently, the acoustic emission is mostly employed for a qualitative assessment of the structure level of damage.

We close our discussion emphasizing on the significance of the feature selection algorithm for SHM methodologies. The crucial step is to extract information related to the damage from sensor outputs. Operational and environmental factors along with material properties and size scales are all determining factors that affect the sensor outputs. The effect of such factors becomes
more pronounced once a more sensitive monitoring method is deployed e.g. acoustic emission. In such circumstances, the SHM designer is advised to define a feature sensitive to the damage mechanisms responsible for the failure in a specific application. Features that quantify the deteriorations in probability distribution of the measurements could disclose the information pertained to the damage regime. We showed an example of such scenario by employing the cumulative information entropy as a sensitive feature to the changes in the acoustic emission regimes during the fatigue degradation of the composites.

5.5 References


Chapter 6. Energy Dissipation and Entropy Production during the Fatigue Degradation

This paper is concerned with a continuum formulation for irreversible energy dissipation that accounts for generated acoustic emissions during the loading of the materials. Within a thermodynamically consistent framework, the coupling between the mechanical, thermal and acoustic fields is formulated. The evolution of the dissipative energy is experimentally measured as the material is degraded. A statistically similar behavior is observed in different forms of the dissipated energy as the material degrade.

6.1 Introduction

Energy dissipation and entropy production are two metrics that describe the irreversible processes occurring in a material subjected to loading cycles [1-4]. Bryant et al. [5] show that associated entropy production is a measure of material’s degradation. Basaran et al. [1] proposed entropy as a quantity that connects the behavior of the structure at dislocation level, e.g. initiation of the micro-cracks, with the macroscopic response of the structure. The underlying physics of the degradation in various applications such as tribological processes [6, 7], friction [8, 9], wear [9-11] and the fatigue problem of the machinery components [12] are reported to be correlated with entropy production. Following the work of the Bryant et al. [5], Naderi and Khonsari [13] quantified the entropy production for characterizing the fatigue degradation [13-14].

Fatigue degradation is a cumulative irreversible process that occurs due to internal friction and initiation and growth of micro-fractures that manifest themselves in different forms of dissipation mechanisms including mechanical hysteresis, heat and acoustic emissions. While heat and entropy generation have been utilized by many to characterize the rate of material degradation and evolution of fatigue damage, the role of acoustic emission (AE) is often neglected, and its
application is typically limited to the detection of the failure with qualitative interpretation of the material response.

Acoustic emission represent the response of a material to the changes of the external conditions generated internally due to deformations, micro-cracks [15], dislocations [16], debonding of inclusions [17], phase transitions [18, 19], recrystallizations, slipping, twining [20, 21] and the interaction between the cracked surfaces. The AE method has been used extensively for detecting the dynamics of fracture in a broad range of the materials. However, the physics of the AE phenomenon is not well understood [18, 22], and it is unclear that how acoustic emissions should be incorporated quantitatively into models of dynamic fractures [23-25]. According to [25], one of the reasons for the inconsistencies in the results of the models and experiments is the lack of considerations of the acoustic waves in most models. Additionally, models that describe the acoustic emissions of the materials are not often based on continuum mechanics [26]. They are typically based on implementation of the approaches such as Fiber-Bundle models [26, 27] or random fuse networks [28].

The premise of this study is that the deteriorations in the integrity of a cyclically loaded specimen is reflected in several forms of dissipative mechanisms that occurs concurrently. We aim at measuring the signatures of such dissipation mechanisms simultaneously as they occur inside the material. The thermal, mechanical and acoustic dissipation energies are quantified experimentally during the life span of the material. To obtain a mathematical understanding of the experimental observations, we also develop a continuum depiction of the irreversible processes of a solid medium including the acoustic emissions and heat generation utilizing irreversible thermodynamic principles.
6.2 Theoretical

We define a continuous medium of the volume $V$ and the differential volume of $dV$ with two distinct states called initial (in equilibrium) and the deformed configuration, respectively. The transformation from the initial configuration to the deformed conditions maps each points on the continuum to a new position. By comparing the distance between two points of the un-deformed body and that of the same point on deformed configuration, one can determine if the continuum is under tension or compression. Considering the solid medium of inelastic materials as a thermodynamic system, the input mechanical work expended due to deformation of the continuum is dissipated through several mechanisms.

In this paper, we assume that three main dissipation mechanisms are plastic energy, heat generation and acoustic emissions. Heat generation is due to inelastic deformation and internal friction within the material under strain. The generated heat dissipates from the body through the three heat transfer mechanisms such as conduction, convection and radiation.

There are several sources for the acoustic emissions at any state of the deformation, regardless of whether it is elastic or plastic. The acoustic emission sources are demonstrated in Figure 6.1 on a typical stress-strain diagram of the material. Internal friction and elastic deformations are of the sources of acoustic emissions in the elastic region of the loading. Microstructural changes, deformation and movement of the dislocations, voids and inclusions, material’s phase transition and recrystallization are also of the sources of the acoustic emissions.

Propagation of the acoustic waves in the material causes time-varying deformations, or vibrations, that are transmitted particle to particle in the continuum. Acoustic emissions are small scale traveling waves or localized vibrations that produce elastic stress and strain fields due to internal restoring forces of the solid medium. A traveling wave inside the solid medium can be
regarded as an acoustic excitation that is transmitted by elastic forces between the neighboring particles of the medium [29]. Such waves can be measured experimentally by attaching a piezoelectric sensor to the surface of the material.

Figure 6.1. Typical stress-strain behavior of the material and the acoustic emission sources at each stage [29].

We postulate that applying external load/deformation to a solid medium, excites the material in two ways. The first is the mechanical excitation that causes a stress and strain field, and the second is due to acoustic emissions that propagates through the continuum. While the mechanical excitations can produce an elastic or plastic response in the material, acoustic excitations tend to be elastic in most solid materials. The propagation of acoustic emissions inside the solid medium can be described by elastic wave propagation [29]. The continuum in the deformed configuration is depicted in Figure 6.2 where both mechanical and acoustic stress fields are shown.
The mechanical field equations can be obtained by writing the governing equations for the continuum. Conservation laws of mass and momentum are required to obtain the equation of motion of the solid medium. Once the equation of the motion are derived, one can obtain the kinetic energy rate as in equation 1. See [30-32] for derivation.

\[
\frac{\partial \rho \left( \frac{1}{2} v^2 \right)}{\partial t} = - \text{div} \left( \rho \frac{1}{2} v^2 \cdot v - \sigma \cdot v \right) - \sigma : D + \rho F \cdot v
\]

where \( \rho \) is the density, \( v \) is the velocity, \( D \) is the symmetric deformation tensor, \( F \) is the conservative body force. The term \( \sigma : D \) is called the stress power which is the rate at which the medium is deforming.

### 6.3 The Acoustic Field Equations

In this subsection the acoustic field equations and the energy transported by the acoustic waves through the solid medium are formulated. These equation are consistent with the work of Auld [29] and Beltzer [33]. Acoustic sources of various nature induce waves that propagates through the solid medium during the loading sequences.

![Figure 6.2 The continuum in deformed configuration.](image)
The solid medium vibrated acoustically by acoustic emissions propagating through the material can be characterized by the particle displacement field, $u^{ac}(r,t)$, velocity field, $v^{ac}(r,t)$, strain field, $\epsilon(r,t)$, and a stress field, $T(r,t)$. The strain-displacement relation and equation of motion are given by equation 2 and 3, respectively [29] where $F$ is the body force and $\rho$ is the mass density of the medium and $t$ is time. equation 2 states that the gradient of the stress induces acceleration to the mass.

\[
\epsilon = \nabla_s u^{ac} \tag{2}
\]

\[
\nabla \cdot T = \rho \frac{\partial^2 u^{ac}}{\partial t^2} - F \tag{3}
\]

The elastic constitutive equation is:

\[
T = C : \epsilon \tag{4}
\]

where $C$ is the elastic stiffness constants.

By considering the particle velocity variable $v^{ac} = \frac{\partial u^{ac}}{\partial t}$, the equation of motion and the stress-strain displacement due to acoustic emissions can be re-written as following equations, respectively.

\[
\nabla_s v^{ac} = \frac{\partial \epsilon}{\partial t} \tag{5}
\]

\[
\nabla \cdot T = \rho \frac{\partial v^{ac}}{\partial t} - F \tag{6}
\]

\[
\frac{\partial T_{ij}}{\partial x_i} = \rho \frac{\partial v^{ac}_{ij}}{\partial t} - F_i \tag{7}
\]

6.3.1 Energy Flux of the Acoustic Wave (Acoustic Poynting Theorem)

For an acoustic wave propagating through a lossless medium, the difference between two points, $p_1$ and $p_2$, on the path of the propagating wave is equal to the rate of the change of the stored energy. Point $p_1$ is located on the part of the solid medium touched by the wave flow and $p_2$ is located on the untouched part. The total energy of the wave front is the sum of the potential
and the kinetic energy of the fraction of the volume which is disturbed by the acoustic wave \( V_{touched} \) in Figure 6.3. This is the declaration of the acoustic Poynting theorem derived in analogy with electromagnetic fields governed by Maxwell’s equation and provides an interrelation of the power supplied by the sources of the waves and the energy lost [29, 33, 34].

Figure 6.3 The propagating acoustic waves through the lossless solid medium. \( p(t) \) is the moving plane in front of the waves which divides the solid into two volumes of the \( V_{untouched} \) and \( V_{touched} \).

The kinetic and potential (elastic stored) energy in the touched region are obtained by equations 8 and 9, respectively. The energy flux vector is the energy crossing the wave front plane \( p(t) \) per unit time and is given by [29, 33].

\[
K = \frac{1}{2} \int_{V_{touched}} \rho u_i^{ac} u_i^{ac} \, dV = \frac{1}{2} \int \rho \sigma^{ac} \, dV \tag{8}
\]

\[
P = \frac{1}{2} \int_{V_{touched}} c_{ijkl} u_{i,j}^{ac} u_{k,l}^{ac} \, dV = \frac{1}{2} \int_{V_{touched}} \epsilon_{ij} \sigma_{ij} \, dV \tag{9}
\]
\[
\frac{\partial E}{\partial t} = \int_{V_{\text{touched}}} \left( \rho \dot{u}_i^{ac} \dot{u}_i^{ac} + c_{ijkl} \dot{u}_{i,j}^{ac} \dot{u}_{k,l}^{ac} \right) dV = \int_{V_{\text{touched}}} \left( \rho \nu^{ac} \cdot \frac{\partial \nu^{ac}}{\partial t} + \epsilon : c : \frac{\partial S}{\partial t} \right) dV \quad (10)
\]

By writing an acoustic power relation, neglecting the viscous power loss, a reduced form of the acoustic Poynting theorem can be written as equation 11*.

\[
\oint_{P} (-\nu^{ac} \cdot T) \cdot n \ dP + \frac{\partial E}{\partial t} = P_s \quad (11)
\]

where the first left hand term is the total power flow outward through the closed surface of \(P\), \(\frac{\partial E}{\partial t}\) is the sum of the kinetic and potential energy in \(V\) and expressed by equation 10. The integrand of the surface integral is acoustic Poynting vector and is equal to the power delivered by the acoustic stress field through the surface \(dP\). In equation 11, \(\nu^{ac}\) is the velocity if the particles of the medium. For obtaining the energy transferred through the surface \(dP\), one should integrate the Poynting vector with respect to time which gives equation 13.

\[
P = -T_{ij} \dot{u}_i^{ac} = -\nu^{ac} \cdot T \quad (12)
\]

\[
E = -T_{ij} \dot{u}_k^{ac} = -u^{ac} \cdot T \quad (13)
\]

where \(\nu^{ac}\) is the velocity of the particles and the \(u^{ac}\) is the displacement. The produced power by the internal sources in volume \(V\) contains two main parts: the stored energy in the form of the kinetic and potential energy as well as the remainder energy which is radiated outwards. The radiated power is equal to the flux of the Poynting vector crossing the surface which determines the boundaries of the volume \(V\). Thus, the Poynting vector represents the instantaneous power per unit area and is by definition the acoustic intensity. This is the amount of energy crossing the unit area in unit time expressed in units of \(\frac{W}{m^2}\) [35].

* If one considers the problem of a propagating wave through a viscously damped medium, then power loss term needs to be added to the right hand side of the equation 10 which equals \(\int_{V} \frac{\partial S}{\partial t} \cdot \zeta : \frac{\partial S}{\partial t} dV\) where \(\zeta\) is the viscosity tensor.
6.4 Conservation of Energy, First Principle of Thermodynamics

The first law of thermodynamics is conservation law of energy and the second law of thermodynamics is conservation of entropy. The conservation law of energy gives an energy balance between all sources of energy transfer into/out of the solid medium and the internal energy as depicted in Figure 6.4 where a schematic of the control volume of a typical specimen under the external work is demonstrated. This transfer of the energy occurs through the boundary of an arbitrary volume of the system [30].

![Figure 6.4](image)

Figure 6.4. A schematic of the control volume of a typical specimen under the external mechanical work with the generated energy fluxes of heat $J^q$ and acoustic emissions $J^{AE}$.

In the thermodynamic analysis of a solid medium under external loading, it is assumed that the density remains constant throughout the loading and the body forces can also be neglected. Once the material is subjected to loading, there are multiple sources of energy transfer into/out of the medium such as heat generation due to the internal friction, mechanical and acoustic deformations are transferred to the environment by conduction, convection and radiation.
The applied work on the control volume consists of two components, one is due to the external loading \( dW^{Me} \) (applied displacement) and the other is due to the propagation of the acoustic emissions through the control volume, \( dW^{Ac} \). Accordingly, the change in the internal energy of the volume can be decomposed to \( dU^{Me} \) and \( dU^{Ac} \) due to the mechanical and acoustical work, respectively. The thermal dissipation mechanisms are also assumed to be due mechanical and acoustic excitations, of which thermal energy fluxes are \( J^q \) and \( J^{AE} \), respectively. We assume that the propagation of the acoustic emissions through the solid medium is capable of generating heat and raising temperature no matter how significant it is comparing to the generated heat and temperature rise due to mechanical excitation of the medium.

The first principle of thermodynamics states that the rate of change of the kinetic energy plus internal energy with respect to time is equivalent to sum of the total work plus all other energy supplied to or extracted from the medium in unit time. The total specific kinetic energy \( \frac{dKE}{dt} \) of the medium is the sum of the specific kinetic energy due to mechanical (equation 1) and acoustic fields (equation 8). The total specific work \( \frac{dW}{dt} \) performed on the medium is the sum of the specific work due to mechanical, \( \frac{dW^{Me}}{dt} \), and acoustic \( \frac{dW^{Ac}}{dt} \) (equation 9) fields.

The rate of change of the kinetic energy, \( \frac{dKE}{dt} \) associated with region \( \partial D \), consists of two terms related to mechanical and acoustic fields which are \( \frac{1}{2} \rho \nu_l \nu_l \) and \( \frac{1}{2} \nu_l^{ac} \nu_l^{ac} \), respectively. Let a region \( D \) bounded by the surface \( \partial D \) in the material medium of volume \( V \) margined by \( \partial V \). The rate thermal energy \( Q \) [30, 31] is received by the region \( D \) is defined as:

\[
Q = \int_V J^{total} dV = \int_D \rho rdV - \int_{\partial D} J^q_{tot} dS
\]  

The total energy fluxes, \( J^{total} \), includes three terms related to internal heat source per volume, \( \rho r \), heat flux by conduction \( J^i_l n_l \), and heat flux due to acoustic wave propagation \( J^{Ac}_l n_l \). The term
\(J^{tot}_i\) consist of the summations of the both terms \(J^q_i n_i\) and \(J^{Ac}_i n_i\). In general, the R.H.S of the equation 14 is the negative (positive) divergence of the inflow (outflow) per unit volume of the heat and acoustic emission through the boundaries of the volume element.

The rate of the work applied on the this domain of continuum \(\frac{dW}{dt}\), includes three terms related to the rate of work done on the continuum due to stress field caused by mechanical excitation \(\sigma_i v_i\), stress field caused by acoustic excitation \(T_i v_i^{ac}\), and the rate of the work done by the body forces, \(\rho v_i F_i\). The first law of thermodynamic reads:

\[
\frac{dKE}{dt} + \frac{dU}{dt} = \frac{dW}{dt} + Q
\]  

where the left hand side of the equation 15 is the sum of the time rate of change in kinetic energy and internal energy. The right hand side is the sum of the time rate of change of the all works and the all other types of energy extracted from or supplied to the control volume. The energy, \(Q\), includes the heat flux and acoustic emission fluxes. \(\frac{d}{dt}\) denotes the materials derivatives.

The integral form of the first principle for the region \(D\) can be written as equation 16.

\[
\frac{d}{dt} \int_D \frac{1}{2} \rho v_i v_i dV + \frac{d}{dt} \int_D \frac{1}{2} v_i^{ac} v_i^{ac} dV + \frac{d}{dt} \int_D \rho (dU^{Me} + dU^{ac}) = \int_{\partial D} \sigma_i v_i dS + \int_{\partial D} T_i v_i^{ac} dS + \\
\int_D \rho v_i F_i dV + \int_D \rho r dV - \int_{\partial D} J^q_i n_i dS - \int_{\partial D} J^{Ac}_i n_i dS
\]  

By applying the Gauss theorem and changing the surface integrals to volume integrals, and rearranging the equation 16, one can derive equation 17 to obtain the rate of change of the internal energy in terms of sums of the stress powers due to mechanical and acoustic excitations and the all other of thermal energy fluxes including heat due to mechanical loading and heat due to acoustically exciting the continuum by acoustic emissions.

\[
\rho \frac{du}{dt} = \sigma : D + T : \epsilon + \rho r - \nabla . J^{tot}
\]  

98
where $D$ is the rate of deformation tensor due to mechanical excitation of the continuum and $\epsilon$ is the rate of the deformation tensor due to acoustic excitation of the continuum.

6.5 Dissipated Energy, Entropy Balance, Second Principle of Thermodynamic

In this section the dissipated energy is derived employing the second law of thermodynamics. This law of thermodynamics declares that the time rate of change of the total entropy $S$ in a solid medium of volume $V$ is greater than or equal to the sum of the entropy flowing in the solid medium through the surrounding boundary and the internal entropy production.

The rate of change of entropy can be written as the sum of two terms [30, 36] as an analogy to equilibrium thermodynamics.

$$\frac{ds}{dt} = \frac{d_{es}}{dt} + \frac{d_{is}}{dt}$$

where $\frac{d_{es}}{dt}$ is the rate of the (external) entropy supplied to the system by its surrounding and $\frac{d_{is}}{dt}$ is the rate of (internal) entropy produced inside the system. $d_{is}$ is zero for a reversible transformation and is positive for an irreversible transformation. The entropy supplied, $d_{es}$, could be negative and positive and zero depending on the interaction of the system with the surrounding.

For the medium of volume $V$, a local specific entropy $s$ is defined as $s_{tot} = \int_V \rho s dV$ which is composed of two parts of $\frac{d_{es}}{dt} = -\int_D J_{s,tot} dS$ and $\frac{d_{is}}{dt} = -\int_V \gamma dV$.

where $s$ is the entropy per unit mass, $J_{s,tot}$ is the total entropy flow per unit area and unit time, and $\gamma$ is the entropy source strength or the entropy production per unit volume and unit time [30, 36]. Using local form of the entropy and by applying the Gauss theorem, we obtain:

$$\int_V \left( \frac{\partial \rho s}{\partial t} + \text{div} J_{s,tot} - \gamma \right) dV = 0.$$ Hence,

$$\frac{\partial \rho s}{\partial t} + \text{div} J_{s,tot} - \gamma = 0, \gamma \geq 0 \quad (19)$$
equation 19 can also be written as:

\[
\frac{ds}{dt} \geq \int_V \frac{r}{\theta} dV - \int_{\partial D} \frac{J^{q_{\text{tot}}}}{\theta} dS
\]  

(20)

Employing the divergence theorem and changing the surface integral into volume integrals equation 21 is obtained as:

\[
\rho \frac{ds}{dt} + \nabla \cdot \left( \frac{J^{q_{\text{tot}}}}{\theta} \right) \geq 0
\]

(21)

By obtaining \( r \) from the Eq. 17, conservation of energy, and replacing in the Eq. 21, we obtain:

\[
\rho \frac{ds}{dt} + \nabla \cdot \left( \frac{J^{q_{\text{tot}}}}{\theta} \right) - \frac{1}{\theta} \rho \frac{du}{dt} - \sigma : D - T : \epsilon + \nabla \cdot J^{q_{\text{tot}}} \geq 0
\]

(22)

With the help of the Eq.23, and by multiplying by \( \theta > 0 \), Eq.24 is obtained.

\[
\nabla \cdot \left( \frac{J^{q_{\text{tot}}}}{\theta} \right) = \frac{1}{\theta} \nabla \cdot J^{q_{\text{tot}}} - \frac{1}{\theta^2} J^{q_{\text{tot}}} \nabla \theta
\]

(23)

\[
\rho \theta \frac{ds}{dt} - \rho \frac{du}{dt} - \frac{1}{\theta} J^{q_{\text{tot}}} \nabla \theta + \sigma : D + T : \epsilon \geq 0
\]

(24)

The inequality in the equation 24 can be written in the form of a as a balance equation for the entropy density. This gives a local mathematical expression for the second law of thermodynamics as in equation 25.

\[
\rho (\theta \frac{ds}{dt} - \frac{du}{dt}) - \frac{1}{\theta} J^{q_{\text{tot}}} \nabla \theta + \sigma : D + T : \epsilon + \gamma = 0
\]

(25)

Next, the rate of change of the entropy should be related to the variation in the properties of the system employing Gibbs relations—written as: [37].

\[
\theta ds = du - dW^{\text{ava}}
\]

(26)

where \( dW^{\text{ava}} \) is the available work [37] defined as the maximum amount of work that could be produced by a system between two thermodynamic states. The available work is equivalent to the change in the stored energy due to increments in acoustic and mechanical strain fields

\[
dW^{\text{ava}} = \sigma dD + T d\epsilon.
\]
Utilizing the Helmholtz free energy, defined in equation 27, a set of physical variables (macroscopic state variables) are incorporated into the equation 26.

\[ \Psi = u - \theta s \]  
(27)

Differentiating equation 27 with respect to time yields \( \frac{\theta ds}{dt} - \frac{du}{dt} = - \left( \frac{d\Psi}{dt} + s \frac{d\theta}{dt} \right) \) and using this relationship, equation 24 can be written as:

\[ \sigma; D + T: \epsilon - \rho \left( \frac{d\Psi}{dt} + s \frac{d\theta}{dt} \right) - \frac{1}{\theta} J q_{cot} \nabla \theta \geq 0 \]  
(28)

For an elastic (reversible) phenomenon, the reversible stress power is defined as \( \phi^e = T: \dot{\epsilon}^e \). In the presence of the plasticity, the total strain can be decomposed in two terms of total plastic (inelastic) strain \( \epsilon^p \) and total elastic strain \( \epsilon^e \). In our study, we decompose the total strain in three terms of the elastic strain due to mechanical loading, \( \epsilon^{em} \), and the dissipative strain due to propagation of acoustic waves inside the continuum, \( \epsilon^{ea} \) and plastic strain, \( \epsilon^p \). The \( \epsilon^{em} \) is known as thermo-elastic strain. One can assume that the dissipative elastic acoustic waves can also be decomposed into two parts: waves originating from mechanical elastic loading of the continuum, \( \epsilon^{eae} \) and waves originating from the mechanical plastic loading of the continuum, \( \epsilon^{eap} \). Therefore, the total strain can be written as in the following equations:

\[ \epsilon^{ea} = \epsilon^{eae} + \epsilon^{eap} \]  
(29)

\[ \epsilon = \epsilon^{em} + \epsilon^{eae} + \epsilon^{eap} + \epsilon^p = \epsilon^e + \epsilon^p \]  
(30)

We choose the free specific energy potential \( \Psi \) as a function of the state variables and internal variables.

\[ \Psi = \Psi(\epsilon, \theta, V_k, \epsilon^e, \epsilon^p) \]  
(31)

where \( \epsilon \) is the total strain defined by equation 30 and \( V_k \) is the internal variables. Using the relation, \( \epsilon - \epsilon^p = \epsilon^{em} + \epsilon^{ea} = \epsilon^e \), one can rewrite equation 31 as: \( \Psi = \Psi(\epsilon - \epsilon^p, \theta, V_k) = \Psi(\epsilon^e, \theta, V_k) \).
Differentiating of the obtained specific free energy yields to:

$$\frac{\partial \psi}{\partial t} = \frac{\partial \psi}{\partial \varepsilon_{em}} \frac{\partial \varepsilon_{em}}{\partial t} + \frac{\partial \psi}{\partial \varepsilon_{ea}} \frac{\partial \varepsilon_{ea}}{\partial t} + \frac{\partial \psi}{\partial \theta} \frac{\partial \theta}{\partial t} + \frac{\partial \psi}{\partial V_k} \frac{\partial V_k}{\partial t}$$  \hspace{1cm} (32)

By substitution of the equation 32 into equation 28, we obtain:

$$\sigma : D + T : \varepsilon - \left( \frac{\partial \psi}{\partial \varepsilon_{em}} \frac{\partial \varepsilon_{em}}{\partial t} + \frac{\partial \psi}{\partial \varepsilon_{ea}} \frac{\partial \varepsilon_{ea}}{\partial t} + \frac{\partial \psi}{\partial \theta} \frac{\partial \theta}{\partial t} + \frac{\partial \psi}{\partial V_k} \frac{\partial V_k}{\partial t} + s \frac{d\theta}{dt} \right) - \frac{1}{\theta} J^{q_{tot}} \nabla \theta \geq 0$$ \hspace{1cm} (33)

For the small strains, the deformation tensor $D$ is assumed to be the total strain rate $\frac{\partial \varepsilon_{em}}{\partial t}$ and the deformation tensor $\varepsilon$ due to wave propagation is assumed to be the total strain rate $\frac{\partial \varepsilon_{ea}}{\partial t}$. Thus, we have:

$$\left( \sigma - \frac{\partial \psi}{\partial \varepsilon_{em}} \right) \frac{\partial \varepsilon_{em}}{\partial t} + \left( T - \frac{\partial \psi}{\partial \varepsilon_{ea}} \right) \frac{\partial \varepsilon_{ea}}{\partial t} + \sigma : \varepsilon^p + T : \varepsilon^{ea} - \left( \frac{\partial \psi}{\partial \theta} + s \right) \frac{d\theta}{dt} + \frac{\partial \psi}{\partial V_k} \frac{\partial V_k}{\partial t}$$

$$- \frac{1}{\theta} J^{q_{tot}} \nabla \theta \geq 0$$ \hspace{1cm} (34)

Assuming a deformation in which $\dot{\varepsilon}^p = 0$, $\dot{V}_k = 0$, and $\nabla \theta = 0$, the thermoelastic laws can be written as:

$$\sigma = \frac{\partial \psi}{\partial \varepsilon_{em}}$$ \hspace{1cm} (35)

$$T = \frac{\partial \psi}{\partial \varepsilon_{ea}}$$ \hspace{1cm} (36)

$$s = - \frac{\partial \psi}{\partial \theta}$$ \hspace{1cm} (37)

We define the total elastic stress—the sum of the total elastic stress due to mechanical loading and total elastic stress due to acoustic loading—as $\mathbf{K} = \sigma + T = \frac{\partial \psi}{\partial \varepsilon} = \frac{\partial \psi}{\partial \varepsilon} = - \frac{\partial \psi}{\partial \varepsilon^p}$. In this definition stress is expressed as the thermodynamic force associated with the elastic strain. In a similar manner the thermodynamic forces associated with internal variables is defined as in

$$A_k = \frac{\partial \psi}{\partial V_k}$$ \hspace{1cm} (38)
After defining the thermodynamic potentials to relate the observable state variables and the associated variables, dissipation potentials are needed to describe the dissipative processes [38]. Employing the state laws (equation 35 to equation 37), the Clausius-Duhem inequality is reduced to:

$$\Phi = \sigma : \dot{e}^p + T : \dot{e}^{ea} - A_k \dot{V}_k - \frac{1}{\theta} J^{q_{tot}} \nabla \theta \geq 0$$ (39)$$

$\Phi$ is defined as the sum of the products of the force variables, $\sigma$, $T$, $A_k$ and $\nabla \theta$ with respective flux variables $\dot{e}^p$, $\dot{e}^{ea}$, $-A_k$ and $-\frac{1}{\theta} J^{q_{tot}}$. $\Phi$ is called dissipation function and can be decomposed into three parts $\Phi_1$, intrinsic dissipation or mechanical dissipation, $\Phi_2$, acoustic dissipation and $\Phi_3$ which is called thermal dissipation due to heat conduction.

$$\Phi_1 = \sigma : \dot{e}^p - A_k \dot{V}_k$$ (40)

$$\Phi_2 = T : \dot{e}^{ea}$$ (41)

$$\Phi_3 = -\frac{1}{\theta} J^{q_{tot}} \nabla \theta$$ (42)

The inequality, equation 39, can be interpreted as the total volumetric dissipated energy by introducing a term $\dot{\phi}$ as follows.

$$\dot{\phi} = \sigma : \dot{e}^p + T : \dot{e}^{ea} - A_k \dot{V}_k - \frac{1}{\theta} J^{q_{tot}} \nabla \theta$$ (43)

The accumulated dissipation energy is then obtained from equation 44.

$$\varphi = \int_{0}^{t_c} \dot{\phi} \, dt$$ (44)

where $t_c$ is the current time at which the material is under loading. One can continue the time until the material fails, $t_f$, and obtain the total accumulated dissipated energy until the failure of the materials.

The volumetric entropy production can also obtained from equation 39 as in equation 45.

$$\dot{\gamma} = \frac{\sigma : \dot{e}^p}{\theta} + \frac{T \dot{e}^{ea}}{\theta} - \frac{A_k \dot{V}_k}{\theta} - \frac{1}{\theta^2} J^{q_{tot}} \nabla \theta$$ (45)
Equation 45 can be interpreted as the product of the thermodynamic forces $X^k$, and the associated fluxes $J^k$, i.e. $\dot{\gamma} = \sum_k X^k J^k$

The total accumulated entropy is then obtained from equation 46.

$$\gamma = \int_0^{t_c} \dot{\gamma} \, dt$$ (46)

where $t_c$ is the current time at which the material is under loading. One can continue the time until the material fails, $t_f$, and obtain the total accumulated entropy until the failure of the materials.

In brief, the total energy dissipation equation 39 includes term pertaining to mechanical, thermal and acoustic dissipation in a medium subjected to stress. We aim at experimentally measure each term in equation 39 to observe the evolution of the energy dissipation for a given test coupon loaded cyclically.

### 6.6 Material and Experimental Procedure

The material tested is aluminum 6061-T6511— with the mechanical, fatigue and thermal properties summarized in Table 6.1— and the specimens are manufactured according to the ASTM STP 566 for use in reverse-bending fatigue tests depicted in Figure 6.5. All of the dimensions are in millimeters.

### 6.7 Bending Fatigue Setup

A schematic of the experimental apparatus employed in this research is shown in Figure 6.6. It consists of a bench-mounted unit containing a variable speed motor, variable throw crank connected to the reciprocating platen with a failure cut-off circuit in a control box and a cycle counter. The crank can be tuned from 0 to 50 mm to apply bending displacement.

The specimen is clamped at one end and the other end is oscillated with a specified amplitude and frequency. The displacement amplitude of the performed experiments starts from the
amplitude of 25.4 mm and decrease in the increments of the 1.27 mm. The frequency of the cyclic loading is 10 Hz for all of the tests.

Table 6.1. Material parameters of the Al 6061-T6 [39]

<table>
<thead>
<tr>
<th>Material parameters of AL 6061-T6</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$(MPa)</td>
<td>$7.04 \times 10^4$</td>
</tr>
<tr>
<td>$\sigma_y$(MPa)</td>
<td>309</td>
</tr>
<tr>
<td>$\sigma_n$(MPa)</td>
<td>398</td>
</tr>
<tr>
<td>$\sigma_0$(MPa)</td>
<td>22.7</td>
</tr>
<tr>
<td>$\sigma_f$(MPa)</td>
<td>443</td>
</tr>
<tr>
<td>$\sigma_c$(MPa)</td>
<td>35.5</td>
</tr>
<tr>
<td>$\varepsilon_n$(mm/mm)</td>
<td>0.10315</td>
</tr>
<tr>
<td>$\varepsilon_0$(mm/mm)</td>
<td>$4.61 \times 10^{-9}$</td>
</tr>
<tr>
<td>$C$(mm/mm)</td>
<td>$3.33 \times 10^9$</td>
</tr>
<tr>
<td>$\beta_0$(MPa)</td>
<td>157</td>
</tr>
<tr>
<td>$\beta_1$(MPa)</td>
<td>382</td>
</tr>
</tbody>
</table>

Figure 6.5 Geometry of the specimen used for fully reversed bending fatigue test. All dimensions are in mm.

Figure 6.6. Schematic diagram of the experimental setup.
6.8 Infrared Thermography Setup

Temperature is measured by means of a high-resolution infrared (IR) thermography camera (MIKRON M7500) capable of measuring temperature within the range of 0 °C to 500 °C. The resolution is 320 × 240 pixel with an accuracy of ±2% of the reading. The sensitivity of the IR-camera is 0.08 °C at 30 °C and it updates the image at a rate of 7.5 Hz. The thermal emissivity of the specimen is increased by painting its surface in black.

6.9 Acoustic Emissions Setup

A PCI-2, a two-channel AE system, continuously measures the acoustic emissions from the specimen during the entire test. It samples up to a rate of 10 MHz. A wide-band sensor, 19.02 mm in diameter (range: 100-900 kHz), is mounted on the clamped side of the specimen as shown in Figure 6.6 Gel-type ultrasonic couplant is used to attach the sensor to the specimen. Pre-amplification and recording threshold are set to 40 dB and 45 dB, respectively. Peak Definition Time (PDT), Hit Definition Time (HDT) and Hit Lockout Time (HLT) are specified as 50, 200, and 300, respectively. The extracted AE feature is the AE absolute energy measured in \( \text{aJ} \) (atto Jules) unit. Post-processing of the measured data includes filtration of the signals of zero absolute energy.

6.10 Quantification of the Dissipated Energy and Entropy: Plastic Energy

One can quantify the plastic work experimentally by computing the area under the mechanical hysteresis loop deploying a uniaxial tension-compression fatigue tester. Recently a number of researchers, in a series of experimental studies, Scott-Emuakpor et al. [39-44], Ozaltun et al. [45] and Letcher et al. [46] on Al 6061—the same material used in this study—measured the plastic energy by utilizing the area of the hysteresis loop and provided the following relationship, equation 47, that covers a variety of the loading modes such as tension/compression [39, 41, 44, 45],
bending [42, 44] and shear modes [40, 42]. Then, the evolution of the hysteresis loop is expressed in equation 49.

\[ N_f = C \frac{\sigma_n (\varepsilon_n - \frac{\sigma_a}{2}) + \varepsilon_0 \sigma_a \left( \frac{2\sigma_a}{\sigma_0} - 1 \right) + \frac{\beta_1}{2} \left( \varepsilon_f^2 - \varepsilon_n^2 \right) + \beta_0 \left( \varepsilon_f - \varepsilon_n \right)}{2\sigma_c \left( \frac{\sigma_a}{\sigma_c} \sinh \left( \frac{2\sigma_a}{\sigma_c} \right) - \cosh \left( \frac{2\sigma_a}{\sigma_c} \right) - 1 \right)} \]  

(47)

\[ W_p = \frac{2\sigma_c}{c} \left( \frac{\sigma_a}{\sigma_c} \sinh \left( \frac{2\sigma_a}{\sigma_c} \right) - \cosh \left( \frac{2\sigma_a}{\sigma_c} \right) + 1 \right) \]  

(48)

\[ W(N) = \begin{cases} 
A e^{\frac{q}{N} N_f} & 0 \leq N \leq 0.2 N_f \\
1 & 0.2 N_f \leq N \leq 0.7 N_f \\
B e^{\frac{p}{N} N_f} & 0.7 N_f \leq N \leq N_f 
\end{cases} \]  

(49)

The above equations are obtained based on an energetic criterion expressed in [39-46], which states that the summation of the strain energy density dissipated per cycle in fatigue degradation is equivalent to the total strain energy dissipated during monotonic fracture. Based on this rationale, the number of cycle to failure can be estimated for the particular material of AL 6061 as in equation 47. In equations 47 to 49, \( \sigma_n \) is the true stress at the necking, \( \sigma_a \) is alternating stress amplitude, \( \sigma_c \) and \( \sigma_0 \) are material parameters for cyclic strain and monotonic strain, respectively. \( \varepsilon_f \) is the true strain at the fracture, \( \varepsilon_n \) is the true strain at the necking and \( \varepsilon_0 \) is a material parameter for monotonic strain test. \( \beta_1 \) and \( \beta_2 \) are the regression slope and a constant of the monotonic stress test, respectively. \( C \) is the material parameter, and \( A, B, p \) and \( q \) are fitting parameters. Tables 6.2 and 6.3 show the material and fitting parameters related to the AL 6061 [39, 45]. Here, we explain how the plastic energy is calculated based on the equation 47 to equation 49. We performed a bending fatigue test on a sample specimen and observe the number of cycles to failure. Based on this observation, given the material and fitting parameters, listed in Table 6.2, the corresponding alternative stress, \( \sigma_a \), is calculated from equation 47.
Table 6.2. Fitting parameters of the Al 6061-T6 [39]

<table>
<thead>
<tr>
<th>Material parameters of AL 6061-T6</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>1.8</td>
</tr>
<tr>
<td>( B )</td>
<td>0.251</td>
</tr>
<tr>
<td>( q )</td>
<td>3.398</td>
</tr>
<tr>
<td>( p )</td>
<td>2.025</td>
</tr>
</tbody>
</table>

To obtain the value of \( \sigma_a \), a nonlinear equation, equation 47, for the corresponding experiment is solved iteratively employing a Trust-region dogleg method [47, 48]. Afterward, the plastic energy per-cycle and the evolution of the strain energy is computed from equation 48 and equation 49, respectively. The above procedure is performed for the eight experiment and the \( \sigma_a \), and \( W_p \) are computed from the eight experiment, respectively. The results are tabulated in Table 6.3. The number of cycles to failure is in the range of approximately \([2 \times 10^3 - 3.5 \times 10^4]\).

Table 6.3. Experimental displacement amplitudes, alternative stress, plastic energy and number of cycles to failure related to the eight experiments.

<table>
<thead>
<tr>
<th>Tests</th>
<th>Displacement amplitude (mm)</th>
<th>Alternative stress ( \sigma_a ) (Equation 47)</th>
<th>Plastic energy per cycle (Equation 48)</th>
<th>Number of cycles to failure ( N_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.4</td>
<td>529.84</td>
<td>0.1676</td>
<td>2145</td>
</tr>
<tr>
<td>2</td>
<td>24.13</td>
<td>518.15</td>
<td>0.1416</td>
<td>2539</td>
</tr>
<tr>
<td>3</td>
<td>22.86</td>
<td>506.67</td>
<td>0.1199</td>
<td>2999</td>
</tr>
<tr>
<td>4</td>
<td>21.59</td>
<td>503.75</td>
<td>0.1149</td>
<td>3129</td>
</tr>
<tr>
<td>5</td>
<td>20.32</td>
<td>480.27</td>
<td>0.0814</td>
<td>4417</td>
</tr>
<tr>
<td>6</td>
<td>19.05</td>
<td>458.91</td>
<td>0.0592</td>
<td>6072</td>
</tr>
<tr>
<td>7</td>
<td>16.51</td>
<td>409.61</td>
<td>0.0278</td>
<td>12910</td>
</tr>
<tr>
<td>8</td>
<td>13.97</td>
<td>348.31</td>
<td>0.0104</td>
<td>34730</td>
</tr>
</tbody>
</table>
The plastic energy is plotted in Figure 6.7 where the decreasing trend of the plastic energy can be observed. It is evident as the amount of the displacement amplitude is reduced, the value of the plastic energy per cycle reduces. Plastic energy is a portion of strain energy during the cyclic loading that is consumed for plastic work and dislocation pile up. It is evident that a lower plastic energy results in higher number of cycles to failure. The plastic energy is not constant over the entire life of the specimen. Figure 6.8 shows the evolution of the plastic energy of each of the conducted experiments based on the equation 48.

It is reported [39, 46] that the strain energy per cycle decreases in the beginning of the fatigue cycles, attains a stabilized value followed by a significant increase in final stages of the life when the failure is imminent. For the trend of the evolution of the strain energy over the life of the material refer to [39, 46]. The three stage trend of the strain energy is formulated by equation 49 [39] using a piece-wise exponential function. This three stages of the evolution of the strain energy is also observable in the trend of the cumulative strain energy diagram depicted in Figure 6.8. The trend of the evolution of the cumulative strain energy is normalized with respect to the value at the time of the failure.
The terms due to acoustic dissipation is defined in equation 43. The absolute energy of the acoustic waves is employed for experimental quantification of these terms. Absolute energy is a 6 bytes value of the $\text{aJ}$ (atto Jules) unit and is a true measure of the energy of the acoustic emission signals. Absolute energy is defined as the integral of the squared AE signal—voltage signal—divided by the reference resistance, $10k - \text{Ohm}$, over the duration of the waveform.

The acoustic emission energy pertaining to the eight experiments are depicted in Figure 6.9. Due to variation in the values of the time axis and cumulative acoustic emission energy ($\alpha J$) axis, the experiments are plotted in these figures (Figures 6.9 (a)-(c)), for it is not possible to present the experiments of the shorter duration with longer experiments on a single graph.
Figure 6.9. Cumulative acoustic emission energy (aJ) versus Time.

Figure 6.10 shows the normalized plot of the cumulative acoustic emission energy versus time where both axes are normalized with respect to the largest associated value. This plot is shown in order to compare the results of different experiments together. It is observed that the evolution of the normalized acoustic emission absolute energy exhibits a three-stage trend, similar to the evolution of the cumulative strain energy trend (Figure 6.8).

The normalized plot of the cumulative acoustic emissions absolute energy reveals similar trends. However, since the experiments are of very different duration in time axis and there exist large variations in the cumulative absolute energy axis, we proceed by examining the standardized representation of the data.

Figure 6.10. Normalized cumulative acoustic emission energy for the eight experiment.
The standard representation of a data e.g. cumulative acoustic emission absolute energy is obtained as following:

\[ z = \frac{x - \mu}{\sigma} \]  

(50)

where \( x \) is the variable to be standardized, \( \mu \) is the mean of the data, and \( \sigma \) is the standard deviation of the data. The standardized data, often called as standard score or Z-score scale, represent the distance between the raw data and the mean value in units of the standard deviation.

We look into the standardized representation of the AE cumulative absolute energy where the mean of the dissipated energy is removed from each experiment’s data and they are divided by the standard deviation. The result is shown in Fig 6.11 (a) Along with each standardized representation of the data, its range should also be presented. Figure 6.11(b) shows the range of the results of the eight experiment in the form of a box and whisker plot. Each side of the whiskers correspond to the largest data points that are not evaluated as outliers. It is apparent that the cumulative dissipated absolute acoustic emission energy corresponding to each experiment demonstrate a persistent evolution trend which reveals that the energy release of the acoustic emission regime follow a specific pattern during the cyclic loading of the specimens irrespective of the displacement amplitude.

The central red marks represent median, the margins of the box show the 25\(^{th}\) and 75\(^{th}\) percentiles. This pattern is similar in trend to the evolution trend of the strain energy depicted in Figure 6.8. The emitted acoustic waves are a portion of the total strain energy in a material under loading that are emitted in the form of a stress wave. In general, the total strain energy can be decomposed to a recoverable and unrecoverable strain energy. The recoverable part is a portion of the total strain energy that if the material is unloaded to a stress-free state is obtainable in the form of a potential energy.
Figure 6.11. (a) Standardized cumulative acoustic emission energy. The standardized time and standardized cumulative acoustic emission energy is negative for data points smaller than the mean of the data. The standardized cumulative acoustic emission energy and time is obtained according to the relation $z = \frac{x-\mu}{\sigma}$ where $x$ is the variable to be standardized, $\mu$ is the mean of the data, and $\sigma$ is the standard deviation of the data. (b) The variation of the acoustic emission absolute energy (aJ) versus the displacement amplitude for the eight experiments.

However, the unrecoverable portion of the total strain energy is a part which is consumed by irreversible phenomena inside the material such as crystalline slip and plastic deformations and flow. To obtain a statistical inference of the cumulative absolute energy data and to ensure that the results are statistically similar, we estimate the non-parametric probability density function (PDF) of the cumulative absolute energy.

The PDF of a random variable or a data such as cumulative acoustic emission absolute energy represent the relative likelihood of the data to attain a given range. The results are presented in Figure 6.12. A normal kernel smoother is also employed in kernel estimation step needed in calculating the probability density functions. The waterfall plot of the estimated PDFs with respect to the displacement amplitude is shown.
Figure 6.12. a) The probability density function of the standardized acoustic emission energy. b) 3D plot of the non-parametric probability density function of the standardized acoustic emission absolute energy for various displacement amplitude.

As it can be observed in Figures 6.12, the accumulated absolute energy over the life of the specimens are represented by the PDFs of similar shape. The non-parametric PDFs of the accumulated absolute energy, are estimated without assuming any prior distribution to the data. The consistencies observed in the trend of the standardized plot, Figure 6.11(a), as well as the PDF of the data, reveals that the acoustic cumulative energy release regime follows repeatable patterns over the life of the specimen under the cyclic loading of different displacement amplitude.

6.12 Dissipated Thermal Energy

In a plastically deformed metal, a part of the applied mechanical work during the deformation processes is converted to heat and rise the specimen temperature [13, 48, 49]. This is conveniently detected using infrared (IR) camera. Figure 6.13 demonstrate the temperature evolution corresponding to the eight performed experiments. For a better representation of the results, the temperature profiles are categorized into three plots based on their duration. A persistent trend in evolution of the temperature profile, is observed under various displacement amplitude.
Figure 6.13. The temperature profile of the eight experiments. For a better representation of the results the tests are presented in three separate images.

The initial stage is accompanied by a rapid rise in the temperature in stage I, followed by a fairly stabilized stage where temperature does not significantly vary. The final stage of the specimen life is associated with high temperature rise due to macro crack propagation and the related plastic deformation. The first stage is associated with large amount of plasticity and internal friction within a short period of time, while the second is the stabilized stage in terms of the amount of the plastic work, and the last stage is accompanied with a large amount of plasticity in the tips of the macro-crack [50]. In Figure 6.13c, it is evident that the temperature increase in the first and third stage of the life of the specimen is not significant due to lower amount of the displacement amplitude. In Figure 6.14, it is observed that the tests of higher load amplitudes, yield greater temperature rise due to effect of higher stress and the associated plasticity.

To compare the data of the different experiments, the normalized trend of the temperature is depicted in Figure 6.14 (a) where the values in both axes is normalized with respect to the maximum corresponding values. It is observed that due to the differences in the mean of the temperature data, the measured temperature profiles are not comparable well.
Figure 6.14 (a) The normalized temperature vs. normalized time. The standardized time and standardized temperature is negative for data points smaller than the mean of the data. The standardized temperature and time is obtained according to the relation $z = \frac{x - \mu}{\sigma}$ where $x$ is the variable to be standardized, $\mu$ is the mean of the data, and $\sigma$ is the standard deviation of the data. (b) The standardized temperature vs standardized time. (c) The boxplot of the temperature related to corresponding to eight displacement amplitude.

Therefore, the standardized temperature is depicted in Figure 6.14 (b) and (c) where the mean of the temperature is removed from the data and the temperature profile of each experiment is divided by its standard deviation.
Figure 6.14 also shows the standardized profile which reveals the consistent three-stage trend over the course of the cyclic bending loading in all of the performed tests. The range of the temperature data is shown in Figure 6.14 (c) as a box and whisker plot. The lower range, represent the ambient temperature of the laboratory at the time of the experiment. It is evident that in general, the span between the minimum and the maximum temperature is larger in tests of higher displacement amplitude and that is due to the higher plastic deformation. In tests of less displacement amplitude, the gap reduces remarkably. Figure 6.15 also demonstrate the probability density functions of the standardized temperature profiles during the cyclic bending fatigue tests. It is observed that the temperature profiles are described by PDFs of similar shape and pattern. Therefore, the thermal dissipation behavior of the specimens under different amplitude displacement are statistically equivalent.

6.13 Conclusions

In this study, we characterize the dissipated energy of the material under loading cycles by employing continuum mechanics principles. The material dissipation energy includes three forms of plastic energy, thermal energy and acoustic energy. These terms are quantified experimentally by performing a series of fully reverse bending tests using AL6061. In the various forms of energy dissipation, a consistent three stages trend is identified. It is observed that the probability density functions of the dissipated energies of all of the specimens exhibit similar patterns over the life of the specimens. Under the experimental operating conditions tested, the material is shown to dissipate the input work through a statistically similar states irrespective of the applied displacement amplitudes. Such results on the various forms of the energy dissipation indicates that as the material degrades, the behavior of the several forms of energy dissipation remains similar.
Figure 6.15 (a) Nonparametric probability density function of the standardized temperature versus standardized temperature. (b) PDF of the standardized of the temperature for eight experiments versus displacement amplitude.

6.14 References


[32] Saouma, V. E., "Introduction to continuum mechanics and Elements of Elasticity/Structural Mechanics."


Chapter 7. Condition Monitoring of MoS₂ Coated Thrust Ball Bearings using Time-Frequency Signal Analysis*

A method for detection of wear in thrust ball bearings coated with molybdenum disulphide (MoS₂) is presented. It employs an energy feature obtained from time-frequency representation of the vibration signal. Extensive experimental studies are conducted to verify the efficacy of the proposed method for fault diagnosis of MoS₂ coating. These experiments are conducted under both oscillatory and unidirectional motion. The results of vibrations are corroborated with the friction coefficient from the onset of the motion until failure develops. Through monitoring of the energy in time-frequency domain as well as the coefficient of friction, three stages of coating life are identified. They are: healthy period, developing damage, and failure. It is shown that the energy feature can detect whenever wear and damage appear and solid lubricant loses its lubrication capabilities.

7.1 Introduction

Many sensitive devices—telescopes, satellites, positioning devices and the like—require very stringent motion control for precise tracking. In many of these applications, ball bearings are used to provide accurate rotary motion. Where liquid lubricants cannot function appropriately, ball bearings races are coated with solid lubricants to provide low friction and smooth motion. Soft metals, layered solids and, in some cases, polymeric materials are used for coating purposes. Among various types of the soft-layered solid lubricants, MoS₂ is the most common because it offers very low coefficient of friction, has low-maintenance requirement, and accommodates wide range of operating temperatures.

* This chapter previously appeared as Kahirdeh A, Khonsari MM, Condition monitoring of molybdenum disulphide coated thrust ball bearing using time-frequency signal analysis, Vol. 132, No. 4, pp. 04166-1-04166-11. It is reprinted by permission of ASME. See Appendix 1 for permission letter.
Since 1940s—when MoS$_2$ was first introduced as a potential solid lubricant—many researchers have concentrated on studying the governing features of MoS$_2$ frictional behavior as well as its wear mechanisms[1-5]. Typically the pin-on-disk tribology tests are used to characterize friction and wear of MoS$_2$. Wear caused by adhesion, oxidation and plowing are addressed in a number of publications, e.g. [6, 7]. Film transfer, which is also an important consequence of wear and debris generation, is discussed in references [8-11] Nanotribology studies using the atomic force measurements on thin films such as MoS$_2$, diamond-like-carbon(DLC) and nanotextured Si(100) are reported in references [12, 13]. The coefficient of friction are reported to be in a good agreement with macro scale [12]. In [13] by employing nanoindentation and nanoscale friction experiments, mechanical and friction characteristics of the nanotextured silicon surfaces is studied via controlled load and sliding speed.

The effects of the sliding speed on the friction and wear of the MoS$_2$ is discussed by Johnson et al. [14]. They have concluded that increasing the sliding speed results in a reduction in coefficient of friction. Effects of the loading conditions and the thickness of carbon sputtered amorphous thin films is presented in [15] where a decrease in coefficient of friction is reported to occur upon increasing the applied normal load. Numerical stress analysis and surface integrity assessment of solids with layered structure is addressed in [16]. The authors conclude that in a layered medium cracks and delamination at the interface are more feasible in a stiff layer in comparison with a more yielding layer.

In addition to the conventional tribology testing methods, recent advances in signal processing methods, data analyses, and expert systems are opening a new horizon in the application of diagnostics techniques to monitoring the performance to machinery components [17-19]. In particular, a number of studies primarily focus on fault diagnostics through the use of vibration
sensors for detection of defect(s) in ball/rolling element bearings and gears [20-23] as well as for structural health monitoring [24, 25].

In contrast to wealth of information on the tribology of liquid-lubricated ball-and-rolling element bearings—a subject that is known as elastohydrodynamic lubrication,— there is a paucity of published research on coated bearings. An analytical study on MoS₂ coated roller bearings with a two-dimensional cylinder-plate finite element model for analyzing the frictional characteristics of MoS₂ coated rolling element bearings is reported by Lovell et al. [26]. Extension to ball bearings requiring three-dimensional formulation is reported in references [27, 28]. In another study of the MoS₂ coated ball bearing, the authors found the coated friction torque to be relatively invariant with velocity and discussed the implications of their use in precision instruments [29]. However, research pertaining to durability of MoS₂-coated bearings is lacking.

Among very few studies on the coating fault diagnosis, in a recent innovative method [30], a chemical diagnostics technique is applied on a solid lubricated system. In another research [31] a structural health monitoring system based on acoustic emission is proposed for wear detection of ceramic coatings. Yet the potential of applying fault diagnosis methods to coated bearings remains largely unexplored.

The focus of this study is on the utilization of the time-frequency vibration signal analysis to indentify different phases of wear that develops during the operational period of MoS₂-coated thrust ball bearings. In this study, the wear of MoS₂ is not artificially created; it occurs naturally during the course of experiments conducted over an extended period of operation.

7.2 Time- Frequency Energy Analysis of the Vibration Signal

The aim of the signal processing is to extract meaningful features from a signal by transforming it into an apt form. Fourier transform is commonly used for signal analysis in
frequency domain to extract the frequencies that may exist in the signal. However, it is incapable of assigning each frequency to the time it belongs. Given that the frequency behavior of many systems inherently changes with time, an alternative method is needed.

A more effective signal analysis tool uses the Time-Frequency (TF) distributions to represent the signal behavior. These analyses project the one-dimensional time signal into time-frequency plane, which is a two-dimensional function of time and frequency.

Using the time domain or the frequency domain signal analysis, various characteristics and features of the signal can be determined including statistical and spectral features. For example, by applying time and frequency domain analyses on the signal—i.e., $x(t)$ in time domain and $x(f)$ in frequency domain—the energy of the signal per unit time, $|x(t)|^2 |x(t)|^2$, as well as the energy of the signal per unit frequency $|x(f)|^2$ at any specific frequency can be obtained. Here, $x(f)$ is the Fourier transform of $x(t)$. Such common analyses cannot describe the characteristics of the signal when the frequency nature of the signal changes with time or is of random nature.

Among different classes of time-frequency distributions (TFD), the energy class of time-frequency transformations is of practical interest. Usually in energy time-frequency signal distribution, the main target is the total energy of the signal at any specified time and frequency. This class of TFDs was introduced by Cohen in 1966 who utilized bilinear transformations.

A drawback of bilinear TFDs is that they intrinsically possess spurious terms. These cross terms appear when the signal under investigation is composed of multiple components. Detail investigation of different classes of TFDs and characteristics of each is beyond the scope of this paper; they are discussed in appropriate detail in different publications [32, 33].
7.2.1 Wigner-Ville Distribution

Wigner-Ville distribution is one of the TFDs in Cohen’s class which is widely used in different engineering disciplines such as speech recognition, biological signal processing, acoustics and earth-quake engineering. The Wigner function was first developed by Wigner in 1932 for the applications in classical statistical mechanics [34]. The Wigner distribution was redefined by Ville in 1948 for signal processing applications and this new transformation is called Wigner-Ville distribution [35].

Wigner-Ville distribution provides a three-dimensional representation of signals in Time-Frequency–Amplitude space, but usually the projection of this three-dimensional representation is shown in two-dimensional time-frequency plane.

The general formulation for the time-frequency representation of a signal is given by [32] and is defined in equation (1).

\[
\begin{align*}
    w(t, \omega) &= \frac{1}{2\pi} \iiint e^{-j\theta - j\tau \omega - j\theta u} \ \Phi(\theta, \tau)s\left(u + \frac{\tau}{2}\right)s^*\left(u - \frac{\tau}{2}\right) du d\tau d\theta \\
    \end{align*}
\]

(1)

where \(s(u)\) is time representation of the signal and its complex conjugate is \(s^*\). \(\Phi(\theta, \tau)\) is the kernel [36] based on definition of which different time-frequency distributions can be obtained. By choosing \(\Phi(\theta, \tau) = 1\), the Wigner-Ville distribution, WVD is produced, which is defined as follows [37, 38].

\[
\begin{align*}
    \text{WVD}_s(t, \omega) &= \int_{-\infty}^{\infty} s(t + \frac{\tau}{2})s^*(t - \frac{\tau}{2})e^{-j\omega \tau} d\tau \\
    \end{align*}
\]

(2)

where \(s(t)\) is time-dependent signal, \(\tau\) is a time shift variable and asterisk denotes the complex conjugation. The desirable mathematical features of Winger-Ville include such properties as time and frequency marginal conditions, instantaneous frequency, time shift, frequency shift, time and frequency support [32]. However, Wigner-Ville distribution has two major drawbacks: it is not necessarily non-negative and it is a bilinear function producing interferences or cross terms for
multi-component signals. In practical applications, the WVD requires smoothing in order to
eliminate the spurious terms. The discrete version of equation (2) is given by equation (3) for the
discrete signals sampled at frequency $\frac{1}{\Delta t}$ [37-41].

$$WVD_{d}(m\Delta t, k\Delta \omega) = 2 \sum_{n=0}^{2N-1} x((m+n)\Delta t)x^*)((m-n)\Delta t)e^{i\frac{-2\pi kn}{2N}}$$

where $WVD(m\Delta t, k\Delta \omega)$ represents the Wigner-Ville distribution of the sampled signal $s$ and
$\Delta \omega$ equals $\frac{\pi}{2N\Delta t}$.

7.2.2 Pseudo Wigner –Ville (PWV) Distribution

Equation (2) requires specification $S\left(t + \frac{\tau}{2}\right)S^*\left(t - \frac{\tau}{2}\right)$ from $-\infty$ to $+\infty$, which is not practical. The remedy is to implement a “windowed” Wigner-Ville representation called pseudo Wigner-Ville distribution and is defined as:

$$PW_{x}(t, v) = \int_{-\infty}^{+\infty} h(\tau) x \left(t + \frac{\tau}{2}\right)x^*\left(t - \frac{\tau}{2}\right)e^{-j2\pi v\tau} d\tau$$

where $h(\tau)$ is a regular window.

7.2.3 Smoothed Pseudo Wigner-Ville Distribution

The Wigner-Ville distribution is quadratic in $x$, which means if $x$ is a sum $a + b$, the
Wigner-Ville distribution of $x$ includes a cross term of $2ab$ in addition to the quantity $(a^2 + b^2)$. This expression can be formulated as follows [39].

$$W_{x+y}(t, v) = W_{x}(t, v) + W_{y}(t, v) + 2R\{W_{x,y}(t, v)\}$$

where $W_{x,y}(t, v) = \int_{-\infty}^{+\infty} x \left(t + \frac{\tau}{2}\right)y^*\left(t - \frac{\tau}{2}\right)e^{-j2\pi v\tau} d\tau$ and $R$ stands for the real part.

In practice, spurious terms can be considerably reduced by smoothing in time and frequency.
The result is the smoothed-pseudo Wigner-Ville distribution (SPWVD) which is defined by the
following equation [32, 36, 41].

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\[ SPWV_s(t, \omega) = \int_{-\infty}^{+\infty} h(\tau) \int_{-\infty}^{+\infty} g(s - t)x(s + \tau/2)x^*(s - \tau/2)ds e^{-j2\pi\omega\tau}d\tau \] (6)

where \* is defined as a convolution with respect to time t. The function \( g(t) \) is the smoothing function in time and \( h(\tau) \) confines the range of the integral in \( \tau \). Restricting the range in \( \tau \) is equivalent to smoothing in frequency. The SPWV distribution reduces to the conventional Wigner-Ville distribution when \( h(\tau) = 1 \) and \( g(t) = \delta(t) \). To use the SPWV for practical experiments that use sampled signals, a discrete form of the SPWV is required as follows [39, 40].

\[ SPWVD_{(n, m)} = \frac{2}{\Delta t} \sum_{p=-Q}^{Q} \sum_{k=-M/2+1}^{M/2} |h(k)|^2 s(n+k)s^*(n-k)\exp(-j2\pi nk/M)g(n-p) \] (7)

where \( \Delta t \) is the length of the data in seconds, M is the size of the frequency smoothing window represented by \( h(k) \), and \( Q \) is the size of the time smoothing window which is represented by \( g(p) \).

7.2.4 Energy of the Signal in Time-Frequency Domain

By integration the joint distribution over time or frequency, a one-dimensional function of frequency or time is obtained. equations (8) and (9) show the integration over time and frequency [36, 41].

\[ \int_{-\infty}^{+\infty} \rho_x(t, \nu)dt = |X(\nu)|^2 \] (8)

\[ \int_{-\infty}^{+\infty} \rho_x(t, \nu)d\nu = |X(t)|^2 \] (9)

where \( \rho \) is time-frequency energy density. Equations 8 and 9 are called time-frequency marginal integration and must be satisfied by the energy density. A two-dimensional integration over time and frequency results in energy in time-frequency plane defined as follows.

\[ E_x = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \rho_x(t, \nu)dt d\nu \] (10)
In this paper, we utilize the energy content of the smoothed-pseudo Wigner-Ville distribution (SPWVD) as a potential feature for fault diagnosis purposes of a solid lubricated ball bearing. This feature is obtained by two-dimensional integration of matrix SPWV according to the TIME and FREQUENCY. As the severity of the faults expands, the energy content of the vibration signal increases significantly, providing useful information on the energy content in time-frequency plane. The time-frequency toolbox for Matlab [42] is used for obtaining the energy feature from SPWV.

7.3 Application to Fault Diagnosis of MoS₂ Coated Thrust Ball Bearing

The fault diagnosis system for wear detection of the MoS₂ coated thrust ball bearings is schematically shown in the Figure 7.1. Vibration signals measured from accelerometers are used to calculate the time-frequency representation of the time domain signal. A feature from SPWV representation of the signal is calculated to assess the condition of the coating. Simultaneous to measuring vibration, the coefficient of friction is measured as a function of time. The information from both of these parallel measurements is used to assess MoS₂ coating performance and its degradation as a function of time.

![Figure 7.1 Modular Architecture for the fault detection system.](image)

7.3.1 Experimental Setup

Figure 7.2 shows the thrust ball bearings and their bearing raceways. The bearings are made of 52100 hardened steel raceways and each bearing include a steel cage and twelve 4.76 mm-diameter steel balls. The dimensions and coating specifications of the coating are summarized in
Table 7.1. Physical vapor deposition (PVD) technique is utilized to coat the races of the thrust ball bearings with MoS$_2$. In a PVD process, the vaporized form of the solid is deposited on the surface in an atomistic level. The deposition procedure is carried out in a vacuum or a very low pressure environment [43].

![Figure 7.2 MoS$_2$ coated thrust ball bearings](image)

Table 7.1. Ball bearings’ dimensions and coating thicknesses

<table>
<thead>
<tr>
<th>MoS$_2$ Thrust Ball Bearing</th>
<th>Outer Diameter (mm)</th>
<th>Inner diameter (mm)</th>
<th>Thickness (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MoS$_2$ coated thrust bearing</td>
<td>31</td>
<td>15</td>
<td>9650</td>
</tr>
</tbody>
</table>

A tribometer manufactured by Lewis Research, model LRI-1A, was used for measurement of friction and wear. Figure 7.3 shows the schematic of this tribometer. This tribometer can perform repetitive oscillatory tests with a swing angle as low as 30° and frequencies as low as 0.1 Hz. The relative displacement of upper and lower spindle is measured using a levered LVDT (linear variable differential transformer) attached to the lower spindle of which sensitivity is 1.614 V/mm and its accuracy is 2.5×10$^{-3}$ mm. A levered load cell connected to the lower spindle of tribometer measures friction torque and calculates the coefficient of friction using equation 11.

$$f = \frac{F \times L}{N \times R_{mean}}$$

(11)
where $F$ represents the force registered via the load cell, $L$ is the load cell lever length, $N$ is the normal load applied on the bearings and $R_{\text{mean}}$ represents the mean radius of the specimen. The data acquisition system I shown in Figure 7.3 can measure coefficient of friction at maximum rate of 0.125 samples per second. Data acquisitions setup consists of a two accelerometers and a four-channel signal conditioner. The test rig was fitted with high-resolution piezoelectric accelerometers (Model PCB-352B, ceramic shear ICP type with sensitivity of 1000±10 mV/g) to measure the bearing vibration signals. One of the accelerometers is mounted on the lower specimen holder and the other is mounted on the upper spindle of machine. The data acquisition board used for the vibration measuring is a DT300 family DAQ board with 16 bits resolution.

Figure 7.3 Schematic of the LRI-1A tribometer.

Five series of experiments are conducted using the tribometer to assess the behavior of the coating over extended period of time. The operational parameters include types of motion (unidirectional or oscillatory), frequency of oscillation, load, and coating thickness as summarized in Table 7.2. The tangential sliding speed (speed of the center of the balls) for Cases 1-3 is $6.02 \times 10^{-3}$ m/s and for Cases 4 and 5 it is $12.04 \times 10^{-3}$ m/s and $18.06 \times 10^{-3}$ m/s, respectively. Assuming that each ball experiences one-twelfth of the total load and using the Hertzian contact theory, the nominal pressure between a steel ball on a plane is 23.6 MPa for 355 N load and 18.8 MPa for 177 N load.
7.3.2 Time-Frequency Analysis for Coating Damage Detection

Statistical time domain vibration analysis alone is not sufficient to detect ball bearings failure accurately and reliably. Since coating wear simultaneously affects both the time and the frequency representation of the vibration signal, a method that can incorporate both of these elements is needed. In this research, MoS$_2$-coated thrust ball bearings are tested under varying loads, types of motion and with different coating thicknesses.

Table 7.2. Summary of experiments performed on MoS$_2$ Coated thrust ball bearing.

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Type of motion</th>
<th>Frequency of oscillation (Hz)</th>
<th>Angle of oscillation (deg)</th>
<th>Load (N)</th>
<th>Coating thickness (Å)</th>
<th>Test duration (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Unidirectional</td>
<td>Speed of rotation 5(rpm)</td>
<td>-</td>
<td>355</td>
<td>9650</td>
<td>3000</td>
</tr>
<tr>
<td>Case 2</td>
<td>Oscillatory</td>
<td>0.5</td>
<td>30</td>
<td>355</td>
<td>9650</td>
<td>1200</td>
</tr>
<tr>
<td>Case 3</td>
<td>Oscillatory</td>
<td>0.5</td>
<td>30</td>
<td>177</td>
<td>9650</td>
<td>1500</td>
</tr>
<tr>
<td>Case 4</td>
<td>Oscillatory</td>
<td>1</td>
<td>30</td>
<td>355</td>
<td>9650</td>
<td>1200</td>
</tr>
<tr>
<td>Case 5</td>
<td>Oscillatory</td>
<td>1.5</td>
<td>30</td>
<td>355</td>
<td>9650</td>
<td>1200</td>
</tr>
</tbody>
</table>

In what follows, the results of the calculation of the energy of the Smoothed Pseudo Wigner-Ville time-frequency representation are used for different types of experiments. The bearing is exposed to a normal load of 177 N and the frequency of oscillation is 0.5 Hz. The MoS$_2$ coating of thrust bearings used in this experiment is 9650 Å thick. Figure 7.4 shows the coating surface at different stages of its life: Figure 7.4 (a) is the fresh coating surface and Figure 7.4 (b) is the coating after 360 minutes of operation while the bearing was healthy. Figure 7.4 (c) shows the lower raceway when the coating is depleted.

MoS$_2$ wear occurs due to different mechanisms such as fatigue, adhesive, oxidative and plowing. As a result of wear, MoS$_2$ debris is produced. A portion of debris creates a transfer film by adhering to the balls, which provide some useful lubrication. The rest remains on the raceways
for a period of time, but is eventually pushed out of the contact area. The right-hand-side arrows on Figure 7.4 (c) show the accumulated debris on the sides of the raceway. As the experiment continues, the debris is ejected out of the raceway and, upon depletion of coating, eventually the balls come into contact with the race metal substrate, triggering the initiation of the failure phase.

Figure 7.4 Three stages of coating life. (a) Fresh MoS$_2$ coated surface. (b) Coated surface after 360 minutes while bearing is operating in healthy regime. (c) Failure of the coating. Arrows show the debris ejected from the raceway and accumulated on the sides of the raceway.

Continuous recording of data during the experiments (duration time of 1500 to 7000 minutes) generates huge data files that are not conducive to simulation of a time-frequency distribution on a personal computer. The PC on which the program is run has an Intel Pentium III Xeon processor 2.49 GHz and a 3GB of RAM. During each experiment, the vibration data is recorded in 10-minutes intervals and saved as a Matlab file data format. Then, The first 2048 points of a ten-minute signal is selected to calculate the smoothed pseudo Wigner-Ville (SPWV) distribution. The result is a $2048 \times 2048$ matrix of the SPWV distribution. This is the maximum number of points to calculate SPWV-TFD that the PC could handle because of memory issues. However, the results with this amount of data for each calculation are satisfying. For instance, the 6000 minutes experiment yields 600 vibration data files, each with the duration of 10 minutes. The 2048 first points of each file is chosen for calculating the SPWV. The next step is to determine the energy in time-frequency plane for the achieved TFD. This procedure is repeated for all of the 600 vibration
files. Finally, 600 points are generated for the 6000 minutes experiment that can be plotted to examine the variation of the energy feature as the test continues. Comparison of this feature with the variations of coefficients of friction provides information on the degradation of the MoS\textsubscript{2} coating.

7.4 Establishing the Feature Potency with Experimental Case Studies

7.4.1 Case1- Unidirectional Rolling Motion

The aim of this test is to investigate the behavior of the MoS\textsubscript{2} coating under the unidirectional load. This test is performed for 3000 minutes under a load of 355 N. The thickness of the MoS\textsubscript{2} coating in this case is 9650Å. The vibration signal is sampled by 2.5 KHz of frequency.

Three broad phases of the operation as identified in Figure 7.5(a) and (b) are: the healthy period (Phase I), the developing damage period (Phase II) and the failure phases (Phase III). The duration of each phase is depended upon the operating parameters as well as the experiment conditions such as load, speed, type of motion (oscillatory or unidirectional), coating thickness, and humidity. Phase I provides satisfactory operation for sensitive mechanisms that demand accurate control of friction, while in Phase II the integrity of the solid lubricant is compromised. Phase III represents the failure of the coating and the performance of the device is no longer determined by the lubrication characteristics of MoS\textsubscript{2}.

Figure 7.5 (b) shows the coefficient of friction as a function of time. The test results reveal that under the conditions tested, the friction remains fairly constant for about 800 minutes of operation after which it begins to experience a rapid rise. The tendency of the coefficient of friction to rise is indicative of a change in the surface characteristic and MoS\textsubscript{2} debris generation. As the test continues, this MoS\textsubscript{2} debris generation accelerates and leads to a significant increase in
coefficient of friction. After around 980 minutes the friction tends to decrease. The reason for this phenomenon can be explained as a result of ejection of MoS$_2$ debris from the raceways.

![Figure 7.5 Case1. (a)-Energy in the time-frequency plane. (b)-Plot of the coefficient of friction unidirectional case. Three stages of healthy period (I), developing damage (II) and failure (III) is apparent.](image)

As a result of wear and MoS$_2$ debris generation, higher values for coefficients of friction are registered as a natural reaction to surfaces of the raceways becoming rougher. Values of the energy feature in T-F plane are demonstrated in the Figure 7.5 (a). The first 800 minutes of this test is considered as the healthy part of the coating life (Phase I) after which the coating starts to degrade. Comparing to the healthy period, the coefficient of friction rises from a value of around 0.05 to almost 0.2. This period, which is called developing damage stage (Phase II), lasts for approximately 180 minutes. At the end of this period, the top and bottom raceways are nearly depleted of solid lubricant. This period of time, is considered to be the failure phase of the MoS$_2$ coating (Phase III). Figure 7.6 shows the depleted raceway in failure phase where the worn area can be easily seen. The white arrows show debris accumulation on the sides of the raceway.
Turning our attention to the Figure 7.5 (a), we note that during the first 830 minutes of operation the energy feature in TF plane is nearly constant. It shows a very distinct increase in its value comparing to the healthy phase of the coating life in the first 830 minutes. It attains a value of 173 \( V^2 \) after 930 minutes of operation comparing to a value of 0.043 \( V^2 \) at the 920 minutes. Subsequently, the coating enters the failure phase in which the raceways are worn. The three phases in coating life, healthy period, developing damage, and complete failure can be easily distinguished from the coefficient of friction graph as well as the energy graph. The boundaries between three phases are somewhat fuzzy because wear occurs continuously. Transfer film from the coating in the raceways to the balls is a possible reason for this fuzzy behavior since the debris generated as a result of wear still provides some lubrication. Up until the time that an appreciable amount of debris leaves the raceways, the available MoS\(_2\) coating, including the generated debris and transfer films, continues to provide some lubrication between the surfaces. The ability to distinguish between different stages of coating life proves this feature an ideal tool for monitoring and fault diagnosis of the MoS\(_2\) solid lubricants. Figure 7.7 shows the transfer film of MoS\(_2\) on the balls in Case 1. MoS\(_2\) particles are distinguishable on entire surface of steel balls in the cage coated thrust ball bearing.

![Figure 7.6 Case1. Depleted raceway after the 3000 minutes](image_url)
Figure 7.7 Transfer film on the balls in Case1 after the experiment.

Figure 7.8 shows the vibration signal in time domain. Severe “spikiness” is observable around 830 minutes as a result of entering the developing damage stage. This manner continues in the rest of the experiment which is an indicator of surfaces becoming rougher. Then, the level of the vibration decreases as the MoS$_2$ debris generated is ejected out of the raceways.

These results reveal that relying just on the time domain vibration signal is not appropriate, since not every peak can represent damage. An underlying reason for why the energy feature provides better indication of the coating condition rather than the raw vibration signal is that it assesses the deteriorations of the vibration signal jointly in both time and frequency domains. These results illustrate that monitoring the energy obtained from smoothed pseudo Wigner-Ville representation of the vibration signal can provide appropriate information to clearly distinguish the stages in which the MoS$_2$ thin layer coating undergo wear.

7.4.2 Case 2-Oscillatory Motion

In this section, the results of a series of experiments are presented that pertain exclusively to oscillatory motion under the conditions specified in Table 7.2. Phases I, II and III are indentified in coating life representing healthy, developing damage and failure period of the coating, respectively and are demonstrated in Figure 7.9 (a) and (b).
Figure 7.8 Time domain vibration signal

Figure 7.9 Case 2. (a)-Energy in the time-frequency plane. (b)-Plot of the coefficient of friction in oscillatory case. Three stages of the healthy period (I), developing damage (II) and failure (III) are detected.

Similar to Case 1, the end of the healthy period is identified by a rise in coefficient of friction. The coating enters its second phase of operation (developing damage) which is transition stage between a healthy period and a subsequent failure. Developing damage starts approximately after 110 minutes of operation and lasts for an almost 110 minutes.
Figures 7.9 (a) and (b) show the energy feature and the coefficient of friction, respectively. As shown in Figure 7.9 (a) and (b), damage in coating takes place in approximately 200 minutes as signified by a rise in the coefficient of friction. The corresponding value of the energy in SPWV time-frequency plane changes from roughly $0.42 \ [V^2]$ in 200 minutes to a value of $640.4 \ [V^2]$ after 220 minutes, thus clearly signifying a step change in the performance of MoS$_2$. Subsequently, the bearing enters its failure phase and its behavior is no longer governed by MoS$_2$. In contrast, the time domain vibration signal in Figure 7.10 shows sharp pulses in around 200 minutes; this behavior continues and even to some extend intensifies around 700 minutes.

![Time domain vibration signal for the first accelerometer](image)

Figure 7.10 Time domain vibration signal for the first accelerometer

The arrows in Figure 7.9 highlight distinct intervals in which coefficient of friction show rising local slopes. A rise in coefficient of friction represents an increased resistance against rolling motion as well as the consequent debris generation/ejection. These alterations in frictional behavior of the coated system are due to the occurrence of wear on the layers of the MoS$_2$ remaining on the raceways. The trend is similar to what happens while wear first appears in developing the damage phase. In each of these intervals, the alterations in surface characteristics
leaves a distinct vibration signature with respect to the healthy period and consequently the energy feature increases in a reaction to such changes. In cases 3-5 the oscillation frequency is varied, and the capability of detection of the damage by the energy feature is assessed. The results are presented in Section 7.4.3.

7.4.3 Cases 3 – 5: Oscillatory Motion with Different Load and Frequency

The following results pertain to three other oscillatory cases under different loads and frequency tests. In these cases, similar to those identified previously, the damage evolution is recognized by a rise in coefficient of friction as well as energy feature obtained from time-frequency representation of the signal and variations in health changes is apparent. Figures 7.11, 7.12 show the results under different frequency of oscillation and load. After an approximately 1840 minute (Figure 7.11 (a) and (b)), simultaneously with the rising in coefficient of friction, the energy feature starts rising and its value reaches 1.63 \( [V^2] \) after 1920 minutes. Such an increase in both plots represents the change in health phase of the coating and transition from healthy period (phase I) to the developing damage phase (phase II). The process continues until in 2060 minutes of operation the energy feature reaches 18.71 \( [V^2] \); this is also a representative of the developed damage and identified as phase II. At this stage performance of MoS\(_2\) deviate from its normal working condition, with quite distinguishable changes that can be seen in coefficient of friction. During a developing damage phase, layers of MoS\(_2\) are detached and the thickness of the coating is reduced in some areas of the top and bottom raceways. Such regions are prone to more wear and damage. Figure 7.13 shows the worn surface of MoS\(_2\) coating in which traces of MoS\(_2\) debris and wear can be observed. “Scratchy surface” is indicative of the reduced thickness of the MoS\(_2\).
Figure 7.11 Case 3. (a) Energy in the time-frequency representation of the signal. (b) Plot of the coefficient of friction, oscillatory (0.5Hz). Five steps of damage developing and failure occurrences are apparent and labeled using roman numerals. Before these steps MoS$_2$ is operating in healthy period.

Figure 7.12 Case 4. (a) Energy in the time-frequency representation of the signal. (b) Plot of the coefficient of friction oscillatory (1Hz). Healthy period (I) and failure occurrences are labeled using roman numerals.
Figure 7.13 Reduced thickness of MoS₂ coating

The level of the energy in time-frequency plane as well as the coefficient of friction increases when surfaces become rougher as a consequence of wear or MoS₂ debris generation, which tend to impede the smooth rolling of the balls. Metal to metal contact can also increase these two factors. The above-mentioned consequences are observable in Case 3 (Figure 7.11 (a) and (b)) after entering the failure stage. The coefficients of friction plot in Case 3 shows multiples of consecutive rises and falls after its first increase in around 1840 minutes. As mentioned earlier, the rises in the coefficient of friction values indicates the alteration in lubrication regime which is due to wear, MoS₂ debris generation, and effectively rougher surfaces. The load on the coated thrust ball bearing in Case 3 is one-half of the load applied in previous cases. This results in a multi-stage wear occurrence which means that the solid lubricant undergoes multiple stages of damage comparing to the one-stage wear which is observed in Case 2 (Figure 7.9 (a) and (b)).

Table 7.3 tabulates the phases in Case 3 where the damage occurs and gives the corresponding coefficient of friction and energy feature. Arrows in Figure 7.11 (b) show the different stages for damage occurrence and rising slope in the coefficient of friction. Five phases identified after a healthy period which are shown in Figure 7.11 (a). Phase II is the first time wear appears on MoS₂ surface which is called damage developing phase. Phases III, IV, V and VI indicate alteration in
surface characteristics inside the failure phase of the MoS\textsubscript{2}. After around 4000 minutes, the solid lubricant is nearly worn and incapable of providing lubrication. Metal to metal contact and abrasive metal debris exists in this phase of the operation.

In Case 4, (Figure 7.12 (a) and (b)), a healthy period of 200 minutes is recognizable after which the developing damage phase forms. A rise in coefficient of friction at this time is indicative of the appearance of damage. At the 290 minutes of the operation while approximately the coefficient of friction has reached its maximum value, the energy feature reaches a value of 11.3\([V^2]\). By comparing the Cases 3 and 4, it is noted that increasing the load and frequency of oscillation decreases the life of the coating significantly. However, in both cases multiple failure occurrences are detected.

Arrows in Figure 7.12 (b) show an increasing trend of the coefficient of friction, indicative of the occurrence of local wear and MoS\textsubscript{2} debris generation. For each of these intervals within which a failure occurs, a significant increase in energy of the SPWV is distinguishable in Figure 7.12 (a). Phase I is identified as the healthy period of the solid lubricant in Figure 7.12 (a) and (b) phase II is developing damage phase after which MoS\textsubscript{2} enters the failure stage of its life. Intervals III-VII are distinguished damage forming stages which are located in failure phase. Case 5 is performed with an increased frequency of oscillation equals 1.5 Hz.

Table 7.3. Phases in which damage occurs and corresponding coefficient of friction and energy in TF plane (Case 3)

<table>
<thead>
<tr>
<th>Phases in which damage occurs</th>
<th>Coefficient of friction in each interval [(min)- (Max)]</th>
<th>Energy of SPWV value ([V^2])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase II</td>
<td>[0.023-0.11]</td>
<td>18.71</td>
</tr>
<tr>
<td>Phase III</td>
<td>[0.023-0.11]</td>
<td>29.26</td>
</tr>
<tr>
<td>Phase IV</td>
<td>[0.03-0.16]</td>
<td>23.29</td>
</tr>
<tr>
<td>Phase V</td>
<td>[0.024-0.123]</td>
<td>8.167</td>
</tr>
<tr>
<td>Phase VI</td>
<td>[0.027-0.074]</td>
<td>53.2</td>
</tr>
</tbody>
</table>

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In Case 5 (Figure 7.14), it is shown that applying higher frequency of oscillation which is 1.5 Hz causes a different trend in coefficient of friction. As it is depicted in Figure 7.14 (b), the rise in coefficient of friction has a lower slope and the damage evolution has a slower developing rate. This trend of damage evolution might be due to the increase in frequency of oscillatory motion. It is observed in Figure 7.14 (b) that the coefficient of friction has multiple stages of slow peaks and valleys, taking place approximately around 230, 470, 810 and 1090 minutes. It is believed that in these four stages, a considerable amount of the coating leaves the raceways. Monitoring the energy feature in these time intervals show distinct values comparing to that of other time periods. However, approximately 130 minutes of healthy period is quite distinguishable and is labeled as phase I in Figure 7.14 (a) and (b).

Figure 7.14 Case 5. (a) Energy in the time-frequency representation of the signal. (b) Plot of the coefficient of friction oscillatory (1.5Hz). Healthy period is labeled (I) in energy plot.

What is promising with this test is that although the MoS$_2$ shows a different behavior as it is undergoing wear and damage, the energy feature can represent the damage evolution coherently. After passing the healthy period and entering the failure phase, in different time intervals, debris generation continues and MoS$_2$ continues to leave the raceways as it is illustrated in the Figures
7.14 (a) and (b). Comparing to the previous case, healthy period duration decreases because of applying the higher frequency of oscillation. In addition to the investigations of the potency of the energy feature calculated from SPWV, the effect of the operational parameters on the coefficient of friction (COF) during the healthy period is studied. Table 7.4 shows the range of the coefficients of friction during healthy period of the 5 cases studied.

The results of the Cases 2, 4 and 5 can be used to analyze the effect of the sliding speed on coefficient of friction since they are performed under the same load and type of motion. The Cases 2, 4 and 5 have an increasing sliding velocity. As it can be inferred from the Table 7.4, increasing in the frequency of oscillation, which is equivalent to increasing in the sliding speed, causes a reduction in the level of the registered coefficients of friction.

<table>
<thead>
<tr>
<th>Case</th>
<th>COF in healthy period [(min)-(Max)]</th>
<th>Approximation of the mean COF in healthy period</th>
<th>COF at transition to the second phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>[0.010-0.024]</td>
<td>0.017</td>
<td>0.036</td>
</tr>
<tr>
<td>Case 2</td>
<td>[0.012-0.040]</td>
<td>0.028</td>
<td>0.040</td>
</tr>
<tr>
<td>Case 3</td>
<td>[0.020-0.054]</td>
<td>0.022</td>
<td>0.064</td>
</tr>
<tr>
<td>Case 4</td>
<td>[0.010-0.026]</td>
<td>0.012</td>
<td>0.020</td>
</tr>
<tr>
<td>Case 5</td>
<td>[0.007-0.017]</td>
<td>0.008</td>
<td>0.013</td>
</tr>
</tbody>
</table>

The minimum, maximum, an approximation of the mostly recorded coefficient of friction as well as the value of the coefficient of friction at the end of the healthy period decreases as the sliding speed boosts in Cases 2, 3 and 5. Case 3 which has the lowest applied load is of the longest healthy period. This represents an adverse effect of the higher load in healthy life of the coating. Additionally, the length of the healthy period in Case 1, which is performed in a unidirectional
type of motion, is higher than those of Cases 2, 4 and 5 that correspond to an oscillatory type motion but with an equivalent load. This reveals that in an equal loading condition, a unidirectional type of test results in a longer healthy period in comparison to that of an oscillatory case.

7.5 Conclusions

In this research, the feasibility of extracting a feature from time-frequency analysis to detect the wear of the MoS$_2$ coating on thrust ball bearings is investigated. Smoothed Pseudo Wigner-Ville (SPWV) representation is selected for calculating the TF distribution. The energy of the signal in TF plane is employed successfully as a monitoring feature. The results of the five sets of experiments establish the potential of the proposed method for detection of the wear of the coating as well as the changes in lubrication regime of the solid lubricant. Three stages of the coating life are recognized during the experiment from start to failure. These stages are called: healthy period, developing damage, and failure. The duration of the each depends highly on the load, type of motion and the coating thickness. In order to show the potency of the feature in damage detection, coefficients of friction of the MoS$_2$ also are measured that show the appearance of the faults on the coating. Both of methods show similar result in detecting the wear occurred on the raceways. In Cases 1 and 2, after the healthy period solid lubricant enters the developing damage and failure appears in one step. This can be recognized by dominant rises in coefficient of friction as well as energy feature. In Cases 3, 4 and 5 the solid lubricant after passing the healthy period, undergo several developing damage and failure occurrences. The multiple failure occurrences are detected by several consecutive rises in coefficient of friction as well as in energy feature. These results support the potency of this feature in reliable diagnosis of the MoS$_2$ operating phases and in recognizing stages in which the lubrication regime in solid lubricant degrade and undergo undesirable variations.
The energy feature demonstrated independency from the operating condition such as type of motion, frequency of oscillation, loads and detects the stage at which the coating starts leaving the raceways. This behavior makes the feature useful for pattern recognition and automatic fault diagnosis software. While in many tribology applications real-time monitoring the coefficient of friction of the coated ball bearings may not be possible, monitoring such feature extracted from vibration signal of the coated ball bearing provides an attractive alternative for coating fault diagnosis purposes.

7.6 References


Chapter 8. Conclusions and Future Plans

8.1 A Brief Summary of Results

As discussed in the previous chapters, the fatigue degradation problem was studied from the perspective of the energy dissipation for a specific material of woven glass/epoxy laminate and aluminum 6061. Two main sources of dissipative mechanisms, i.e. generated heat and acoustic emission, were examined experimentally as the specimens degrade due to fatigue. Damage modes and failure mechanisms were identified and observed by employing SEM analysis. The evolution of the energy dissipation as the laminates degrade, was monitored that resulted in identification of the three main stages of the life of the laminates.

To ensure that energy dissipation—e.g. acoustic emission and heat— is a reliable tool to monitor the degradation phenomenon in various experimental conditions, statistical analyses were performed on the acoustic emission signatures and revealed that acoustic emission regimes follow the same statistics. The PDF of the acoustic emission signatures including energy, counts showed a power law in multiple decades with a cross-over as the severity of the damage modes increase and failure is approaching. Observing scaling laws that are independent from the operating conditions suggests universality in the statistics of the AE signatures. The reason behind this universality is the consistent damage forming mechanisms and the fact that there exists a critical damage level beyond which the material fails.

Later, to measure and quantify the damage based on the response of the laminate, an entropic damage indicator was defined that is based on the cumulative information entropy of the acoustic emission counts. Examination of the cumulative information entropy of the AE cumulative counts identified the stage where incipient damage takes place and is sensitive to the development of the damage mechanisms involved in the failure of the woven laminate. More information regarding
the states of the damage was extracted from the derivatives of the cumulative Shannon entropy of the AE cumulative counts.

Having observed the experimental evidence on the capability of the dissipation energies in damage diagnosis, the dissipated energy and thermodynamic entropy generation was formulated employing irreversible thermodynamic principles. The material dissipation energy includes three forms of plastic energy, thermal energy and acoustic energy that were quantified experimentally by performing a series of fully reverse bending tests. It was observed that the probability density functions of the dissipated energies of all of the specimens exhibit similar patterns over the life of the specimens and the material was shown to dissipate the input work through a statistically similar states irrespective of the applied displacement amplitudes.

In another work related to the energetic approach in health monitoring of the structures and mechanical components, the vibrational energy was employed to diagnose the failure of the coated ball bearing. Through monitoring of the vibration energy in time-frequency domain three stages of coating life were identified. It was shown that the energy feature can detect whenever wear and damage appear and solid lubricant loses its lubrication capabilities.

8.2 Recommendations for Future Work

The following recommendations are made for future works:

- In Chapters 2-6, the experiments were performed in the range of the low cycle fatigue. The problem of the high cycle fatigue can be investigated by performing the experiments in the range of the high cycle fatigue. The efficacy of the hybrid method employing the infrared thermography and acoustic emissions should be investigated in loading conditions that results in high number of cycles to failure.
- In Chapters 2-5, different damage mechanisms of the Glass/Epoxy laminates were identified through SEM analysis of the fatigued specimens. Advanced signal analysis techniques can be employed in order to distinguish between the measured acoustic emissions signals. Such analysis can reveal the characteristics of the acoustic signals coming from different damage modes such as matrix cracking, or fiber breakage. Pattern recognition techniques can be employed to distinguish between different modes of the damage in the laminate.

- In Chapter 4, the criticality of degradation was investigated employing statistical analysis on the acoustic emission energies measured from the fatigued samples. Such statistical analysis can be performed on the acoustic emissions waiting times. Waiting times are defined as the difference between the times of the recording of two consecutive acoustic signal.

- In Chapter 6, the energy dissipation of the material during the fatigue degradation was mathematically derived and the three terms of the energy dissipation including mechanical, thermal and acoustic dissipations was experimentally measured. Numerical simulations can be considered to simulate the energy dissipation in the course of the fatigue degradation.

- In Chapter 7, a method for health monitoring of the coatings based on the energy of the vibration signals were introduced. Pattern recognition techniques can be applied on the method in order to automate the health monitoring procedure.
Appendix 1. Copyright Letters

Title: Dissipated thermal energy and damage evolution of Glass/Epoxy using infrared thermography and acoustic emission

Author: M. Naderi, A. Kahirdeh, M.M. Khonsari

Publication: Composites Part B: Engineering

Publisher: Elsevier

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