Aluminum Fatigue: A literature review covering its influence on engineering from design to end of service

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(ABSTRACT)

This article is an examination of the field of fatigue research on aluminum alloys. It covers the historical development of the field of fatigue from its creation in the 1830s to modern times. The remainder of the paper is a survey on aluminum fatigue and research that covers the entire span of the design process. This includes research into the effects of manufacturing methods on the fatigue of parts and alloys. This is followed by analysis on methods of monitoring fatigue damage while a system is in service including sensors, methods of inspection as well as structural health monitoring systems and how they contribute to the understanding of fatigue or the mitigation of its effects. Additionally, methods of maintenance and repair are examined with focus the mechanisms they exploit to retard crack propagation and extend the fatigue lifetime of the part or system. Overarching themes of analysis across all areas covered include the motivation of the research as to whether it is meant to advance the understanding of the mechanisms of fatigue or to compensate for the lack of understanding of these mechanisms.

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(GENERAL AUDIENCE ABSTRACT)

The process of metal fatigue, where a material gradually loses strength due to repeated stresses below those that cause instant failure, is a major source of failure in all fields. In this paper I review the state of research into this phenomenon focusing first on the history of research into this. Additionally, I survey papers covering research into how fatigue effects engineering from the design and production of a system to its inspection, maintenance, and repair while it is in service. I also investigate overarching themes in these fields of research where motivation is often split by a desire to improve understanding of the phenomenon or to mitigate the level of uncertainty caused by a lack of accurate ability to predict the how long before fatigue will cause the system to fail.

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List of Abbreviations

AM	Additive Manufacturing
ASTM	American Society of Testing and Materials
CFRP	Carbon-Fibre Reinforced Polymer
DTD	Damage Tolerance Design
FEM	Finite Element Method
FSW	Friction Stir Welding
LCF	Low Cycle Fatigue
NDE	Non-Destructive Evaluation
NDT	Non-destructive Testing
OLM	Operational Load Monitoring
SHM	Structural Health Monitoring
SPR	Self Piercing Rivets
UAS	Unmanned Aerial System

Chapter 1

Introduction and Approach

The most prevalent cause of mechanical failure is fatigue, with some sources citing it as being responsible for 90 percent of these incidents [1, 2]. The phenomenon of fatigue can be defined broadly as the reduction in material performance over time due to the presence of cyclical or fluctuating stresses [3]. The current consensus on the mechanism of fatigue failure in nonferrous metals, including aluminum, is the nucleation and then growth of cracks until the material fractures [4]. This understanding is based on nearly two centuries of continuous research into the phenomenon, with the volume of research still growing today.

In fatigue studies, Aluminum alloys feature prominently for various reasons. Mainly due to the continual increase in the use of Aluminum over the past hundred years due to its general effectiveness as a low-weight material, especially in the transport industry where higher fuel economy demand weight savings [4, 5]. This focus on efficiency has also led to a desire for greater accuracy in fatigue life and damage predictions to allow design margins to be narrowed, saving critical weight. However, in structural design courses, the effects of fatigue are almost entirely ignored. So, this review was done to investigate current and past knowledge of fatigue in aluminum and how its consideration affects the engineering process over the entire life of a system, from initial design to maintenance and repair.

1.1 Areas and Approach

1.1.1 Historical Research

This paper will include an abridged history as a mechanism for establishing an overview of the relevant topics that are visited in later sections. While not an area of focus in this review, in the analysis of the research history, it is noted that, like most history, disagreements about where concepts were developed, what events/developments were the most important, and historical communication difficulties that hindered collaboration are present. An easy example of disagreements can be found simply in who defined the process as ”Fatigue” with competing claims from a Frenchman Jean-Victor Poncelet, Arthur Morin, an Englishman Frederick Braithwaite, and a Mr. Field, with current consensus leaning towards Mr. Poncelet [6]. Of additional note is the motivation behind general advances and specific research being linked to recent incidents of fatigue failure over time. The interest in this section, apart from introducing concepts that are still used and expanded upon in today's research, is to see general trends in the field that have persisted for decades.

1.1.2 Manufacturing Related Fatigue Considerations

In evaluating how fatigue must be considered throughout the engineering life cycle of a system, the first area I investigated was manufacturing and assembly effects. This was done by surveying the current research into aluminum fatigue manufacturing, organized by the manufacturing process used and how that affects the fatigue properties of the resulting material or part. In this, most of the work consists of how each method affects or induces flaws in the material. In my analysis, I focus more on more general traits of the method that affect the fatigue and variations in specific methods that affect the fatigue life of the part. The avoidance of comparison between distinct methods is mainly due to the performance of each method very often depending on the specific part being manufactured. Additionally, the means of attachment or joining of components as part of the assembly process was included, as it is these areas where fatigue failure is most common [7].

1.1.3 Fatigue Monitoring

Given the sometimes-catastrophic effects of fatigue damage and the well-cataloged history of difficulty in predicting it, the investigation into methods of detecting damage has been a focus for as long as the field of fatigue research has existed. Currently, the techniques and practices dedicated to detection can be divided into two separate disciplines: offline inspection and in-service health monitoring. Implementing offline inspections to detect fatigue has long been the best failure prevention method. Inspections, however, result in loss of operational time, so creating methods or apparatus that reduce this operational loss remains a prominent focus of research. These improvements tend to follow two approaches: reducing individual inspection time with faster methods or increasing the damage detection threshold allowing for the detection of more minor flaws in earlier stages of growth, thereby reducing the required frequency of inspections.

Alternatively, inspections can be nearly eliminated in areas covered by in-service structural health monitoring systems. These systems conduct constant, in-service monitoring of service loads or damage detection at vulnerable areas, reducing required inspection time. This chapter of the review was separated into two sections: the sensors that develop data for structural health monitoring, SHM, systems and the systems that make use of the data. These means of detection and sensing are compared with more conventional inspection approaches and reviewed in their utility in SHM. In reviewing the subsequent use of generated data, focus on the methods used and the desired end. As regards the means, this includes data post-processing to increase the utility or reduce the data size of sensor readings as well as the models, whether physics, statistical or computational, used to generate meaningful structural health information from the readings. The use of the output for existing damage detection or predicting future damage to the monitored system or others like it is also considered.

1.1.4 Maintenance and Repair Considerations

With the detection of fatigue damage, the most effective method of eliminating the risks or effects posed by the damage is to replace the damaged part with a new one. However, this is often not possible due to the part no longer being manufactured, the cost of the replacement being prohibitive due to difficulty in removal and installation, or simply the cost of the part being too great. Therefore, the ability to conduct repairs has been an essential part of engineering regarding fatigue, especially in areas where it has proven difficult to accurately predict the fatigue lifetime of a part. So, conducting a repair increases the remaining fatigue life in the part and the system allowing continued operation. The economic advantage in repairing fatigue damage has been considerable and resulted in commensurate levels of research into the topic. Most of this research is oriented towards analyzing and modeling the extension in fatigue life resulting from the various repair methods to compare their performance better.

Chapter 2

History and Overview of Aluminum Fatigue Research

The history of aluminum fatigue began properly with the widespread adoption of the Duralumin alloy of aluminum in the 1910s, as before this, the available alloys were poorly suited to industrial applications where prominent failures occurred [5]. However, a history beginning at this time would omit several critical developments in the field of metal fatigue that are important in later years, so research on metal fatigue from the field's genesis to the 1910s is included for continuity in the context of the development of the area. While vague conceptions of what would become known as material fatigue existed in the failure of masts of ships after prolonged use or the knowledge that a metal rod can be broken easily by repeatedly bending it, the proper investigation only began when the widespread failure of parts at loads below their strength according to contemporary understanding drove the need to solve the issue [8, 9].

2.1 Industrial Era 1840s-1910s

Development in this era focused on iron and steel alloys and their application in the railroad industry and then the early automotive industry [9]. This focus on transport is a constant throughout fatigue research history. Unlike previous applications, fatigue failure of train carriage axles, rails, or other parts often resulted in disaster. The most noteworthy was an axle failure in Versailles, France, that resulted in sixty lives lost [8, 9, 10, 11]. The accident at Versailles in 1842 is almost universally referenced as the incident that began the drive into fatigue research, but it was not unique. Rail accidents were so prevalent that newspapers carried columns referencing the worst accident of the week until 1887 [12]. The intense public interest generated by these accidents, similar to all that occurs with transport accidents today, led to public demands for greater safety that coincided with manufacturer and operator interest in greater reliability and led to the sustained development of the field.

In evaluating information from this era, it is important to note that most research and regulation was made by the companies themselves, especially in the US and UK. This meant advancements in ”best practice,” where a great deal of knowledge in mitigation and compensating for fatigue was concealed for competitive advantage, especially regarding specific manufacturing or design practices. This led to a greater emphasis on the available reports of state-run labs like in Germany [12].

2.1.1 Modeling/Understanding

In this period, there was minimal advancement in models to accurately predict fatigue life. Most of the work was phenomenological, based on the large volume of experimental investigation showing qualitative relationships on what factors influence fatigue, but little, if any, empirical definition of these relationships. However, the discovery of many of the relationships that would later serve as a basis for future modeling efforts were laid out, and the fundamental physical mechanisms of fatigue damage were observed if not identified.

Shortly after the Versailles crash, W.J.M. Rankine, of Thermodynamics fame, made his sole contribution to fatigue study in a paper noting that failures ”preferred” to appear at areas of stress concentration. Simultaneously, work done by Morin identified cracks at the failure location but critically made no differentiation between these fatigue cracks and brittle fracture cracking occurring under static loads [9]. Inspections by sophisticated microscope by R. Stephenson in 1850 conclusively established the micro-structure of metals as crystalline in nature [9]. Later observations by Ewing in 1903 of areas of plastic deformation, what he termed ”slip bands” as a manifestation of fatigue, was a crucial step in understanding the micro-structural mechanisms of fatigue damage [12, 13, 14]. These discoveries of prominent mechanisms in the fatigue process would be expanded later to reach the current understanding.

The contribution of Wohler in the 1850s and 1860s to understanding fatigue cannot be understated. He is responsible for the discovery of many fatigue relationships but would leave the work of stricter definition of these relationships to later engineers. Despite this, he managed to clearly articulate how fatigue life is most influenced by the stress amplitude [12, 15]. The next big step in understanding is in Bauschinger’s work that emphasized the elastic limit varying by cycle in the 1870s [8, 12, 15]. The remaining work of this era in relating fatigue to material properties focused on relating life in terms of load cycles remaining before failure to stress amplitude, max stress, ultimate strength, and tensile strength. Multiple models were developed by Gerber in 1874, Goodman in 1899, and Soderberg in 1900, each with varying accuracy [16, 17].

Early work on stress concentration was done sequentially by Wohler, then Bauschinger, and then Foppl confirmed that geometric concentration of stress induces earlier fatigue failure [16]. Specific work on the mathematical modeling of stress around areas of concentration was done first on circular holes by Kirsch in 1898, elliptical holes in 1913 by Inglis, and notches approaching 0°to approximate cracks in 1907 by Weighardt [16]. Additional work of note includes Kommers noting in 1912 that polishing improves ultimate strength [18]. In 1913, Stanton and Pannell identified welds as a location susceptible to fatigue [14].

2.1.2 Design and Manufacturing Practices

The initial design philosophy for mitigating fatigue was to create a part with infinite fatigue life based on material property safety factors. This practice used safety factors based on yield, or ultimate strength [9, 17]. The first material standards were advocated for by Wohler and implemented in Germany in 1881 with laws mandating the tensile and yield strengths of iron and steel [12]. Apart from this standard, most safety factors employed were proprietary or unique to specific alloys and designs. The results of these safety factors varied, as well as their implementation. The finding of the fatigue limit of the steel, the stress level below which the part has infinite life, formed a fixture of the design philosophy of this period. August Wohler argued the benefits of a finite life design process during his era into the 1870s. However, this would only be embraced more than 50 years later when applications that infinite life design was unsuitable arose.

Regular and systemic inspections were another core practice instituted in this era to curb fatigue failure. The first formal regulation came in the form of mandated inspections, with the first notable example being stagecoach axles after 70000km service in 1843 France [9, 11, 12]. Inspection at fixed intervals generated positive results with ”3.4 times as many axles condemned by inspection as broke in service” (Stephens et al. [19])[11]. Other regulations to help prevent fatigue failure include the mandate of smooth area transitions in axles to negate the common occurrence of fractures at these transitions [11].

2.1.3 Experimental Testing

A German mine administrator conducted the first investigation into fatigue recorded; where after observing the failure of hoist chains in service; he constructed an apparatus to repeatedly hoist the service load until chain failure and published the number of hoists completed before the chains failed [9, 17]. Of interest is that this first example of fatigue testing is how it was conducted under an entirely known service loading that is applied in a method nearly identical to that of regular operation, using actual service components resulting in immediately valuable information, something that many fatigue tests in the subsequent centuries would envy.

Wohler’s contribution to experimental fatigue testing procedure was extensive. For his investigations, he developed strain sensors and experimental setups for fatigue testing of scale model rail-car axles in torsional, axial, and bending loads. Most significantly, he laid out his data in terms of S-N tables, which were later plotted on linear axes by Spangenberg in 1874, and finally plotted on a log-log axis by Basquin in 1912 to create ”Wohler curves” [8, 12, 13, 16]. The 1860s saw the establishment of laboratories dedicated to studying material properties, some with specific emphasis on fatigue in Britain and Germany. The number of these labs and their size continued to grow throughout this era..

The end of this period can be marked by several changes in the field of research. First is in the number of scientific and engineering publications on fatigue doubling in the first decade of the 20th century, then again in the next [9]. Changes in experimentation occurred with a shift from specimens of simple shapes to the testing of production components or facsimiles due to the difficulties in relating the specimen test conclusions to their application in design. The change in design philosophy from the focus on infinite life, usually based on the fatigue limit of steels, to finite life, where the part is designed to have a specific fatigue life. In theory, more detailed investigation focused on the nature of fatigue damage rather than just the performance loss it causes, especially on material cracks and fracture mechanics. Additionally, the focus shifted from the rail industry, and steel/iron to aircraft and aluminum alloys [9].

2.2 Age of Flight (1910s-1960s)

Until the process for economically extracting aluminum from bauxite was created, aluminum was considered a precious metal [5]. This precluded it from serving in a capacity where fatigue damage was likely to manifest. Additionally, before the development of aircraft, there was never an industrial application that put such an emphasis on strength to weight which is aluminum's most important property [20]. This use of aluminum alloys ad the aircraft industry invalidated some areas of previous design practice. In design, the impracticability of infinite life and fatigue limit design to aluminum alloys and aircraft required a new methodology [21]. Further, the much greater emphasis on weight in aircraft compared to ships and trains, rendered the extremely conservative safety factors that typified design at the time either infeasible or uneconomical, incentivizing better refinement of fatigue life to allow narrower margins in the design [7].

2.2.1 Modeling/Understanding

During this time, more advancements in modeling fatigue were made, often due to new engineering practices requiring these better models. A key proposal on modeling the accumulation of fatigue damage came from Arvid Palmgren in 1924. It was later developed independently by Langer, Serenson and given renewed interest by M. Miner in 1945 to create the Palmgren-Miner model that is often used today with only minor modification [12, 13].

This era also saw the fundamentals in modeling the loading and resultant stress/strain distributions laid out. Important work came from Thum in the early 1930s in creating the Elastic Stress Concentration factor, which helped generalize the current thinking to better work for arbitrary loading and dimensions. An important follow-up to previous work came from Neuber and Ohman in 1937 on relating local plastic behavior to elastic stress concentration, developing comprehensive concentration factors [12]. Later in the 1950s, Manson and Coffin, independently of each other, showed that cyclic plastic strain is the source of fatigue damage and effectively created the specialization on Low Cycle Fatigue [8, 12, 22]. Additional work was done to place a more statistical nature to fatigue research due to the difficulty in positing precise evaluations changed toward providing the probability of failure at certain cycle-counts, rather than at what cycle-count failure will occur. However, these gains proved somewhat short-lived, and statistical focus shifted to variations in material properties rather than the more component-centric view [18].

In understanding the micro-structural aspects of fatigue damage, Ewing's discovery of slip bands was a valuable point to expand on [12, 13, 14]. Later work by H.J. Gough and D. Hanson found these ”slip-strips” form below yield stress and that crack formation often occurs at these locations [14]. Additional work demonstrated that material flaws, cracks, pitting, voids, and dislocation as significantly lowering the fatigue life of a material [14, 23]. Early work on the fatigue-fracture relationship from A.A. Griffith in 1920 demonstrated reduced strength due to the presence of these microscopic flaws [8].

Griffith later defined the fatigue-fracture relationship between crack size and stress at the fracture [8]. However, this work was largely under-exploited in fatigue studies until crack propagation at the corners of square window panels resulted in the crash of two British Comet jetliners in the 1950s. These two failures, occurring in 1954, feature in nearly all recitations of important fatigue history [24]. Followed by near simultaneous developments in optical and electron microscopy and X-Ray fractography allowed detailed observation of these micro-structures, assisting research. George Irwin expanded on Griffith's work using linear-elastic fracture mechanics to apply his work to ductile materials like metals [22]. Irwin's work was expanded upon shortly after by Paris and Erdogan, who defined a relationship between an arbitrary series of loading cycles and crack growth in 1960, now known as the Paris Law [8, 12, 22].

The uncertainty of these methods increased the smaller the crack was, eventually leading to small crack growth being split into its own area, distinct from large crack growth[11, 25]. In these areas, large crack growth was reasonably well defined by the late 60s, with crack initiation and small crack growth being areas that would be further explored later [11, 26].

2.2.2 Manufacturing/Regulation/Design

In the first half of the 20th century, great emphasis was placed on research into the development and manufacture of materials with greater fatigue performance [18]. Early attempts that focused on improving the yield strength resulted in some cases where fatigue performance was reduced significantly. A notable example of this relationship is the 7000 series aluminum alloys used in the Lockheed Electra in the 1950s, where despite increased yield strength, its fatigue performance was worse than the earlier 2000 series [24]. The earlier discovery of this led to investigation into specifically improving the fatigue performance of materials [12, 14]. One of the earliest methods of improving the fatigue performance of alloys was the use of shot-peening, where the surface of a part is pelt thousands of times by steel balls, the "shot," to induce beneficial residual compressive stresses near the surface, improving the fatigue properties [12]. Other methods, such as flame-hardening and case hardening, were developed in the early 1930s and 1940s.

As aircraft designs became more complicated through the 40s and 50s, the expected lifetime also increased with the need for aircraft to operate more often for longer [26]. Additionally, safety factors that previously worked became less relevant as high-strength alloys very often did not have a corresponding increase in fatigue performance, as previously mentioned. One method of dealing with uncertainty was the fail-safe design strategy, where any single failure would not compromise the whole system's ability before repairs/replacement can be done [14, 26]. This method was conservative, very much meant to account for the limited accuracy in fatigue life predictions. In another design direction, the Safe-life design strategy was based on safety factors built on load/operation cycles rather than material properties. However, the safe-life design was made difficult by the same method, rarely being consistently conservative or consistently un-conservative between designs [12, 27].

2.2.3 Experimental Testing

This era saw a significant expansion in testing to evaluate models and new materials to better compare the fatigue performance of new parts and materials. Fatigue tests and experiments largely became split into tests done on standardized specimens for evaluating materials and those done on operational components or systems to evaluate designs. The experiments on standardized specimens focused on evaluating the fatigue performance of materials and production methods to develop standardized fatigue properties for the material. Full-scale or miniaturized fatigue tests of operational parts or systems were done to establish the likely fatigue lifetime of the system or to identify specific features that are susceptible to fatigue damage Grover [26].

During WWI, the first full-scale fatigue tests of aircraft were conducted in Britain [12]. As new methods of increasing the fatigue life and improving related fatigue properties developed in the 20s and 30s, tests were done to evaluate the fatigue performance of these materials in line with the current knowledge. A significant development in this period is in the testing of variable load histories, and their effect on the fatigue of the material, exemplified by such work as that of Gassner in 1939 [12]. Variable load testing was necessitated primarily due to aircraft load histories having much greater variety than railroads, which were previously the focus of testing. Variable amplitude service load history testing quickly became standard but was prevented from very widespread use due to the cost/complexity the system required [18]. Increased accuracy in testing was facilitated by developments such as the electrical resistance strain gauge in 1939 [12].

The first tests focused on crack propagation were conducted in 1936 by Prof. de Forest but were isolated in the field [12]. Greater interest in crack growth concepts in the 1950s and 1960s led to the systematic investigation into crack growth rates in fatigue loading scenarios began [16]. These tests were commonly done in line with Paris' law or others similar to develop the database of coefficients used to predict crack propagation under various loading schemes. This focus on crack propagation and formation would take on increased importance later, with the introduction of the Damage Tolerant Design philosophy by the US Air Force [12, 22].

2.3 Onset of Computing (1960s-1990s)

At the start of this period, a usefully generalized definition of fatigue was published by the International Organization for Standardization: "Fatigue is a process of progressive localized permanent structural changes occurring in a material subjected to conditions that produce fluctuating stresses at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations." The improved understanding of fatigue in this period will be contributed to by the full marriage of the concepts of crack growth, and fatigue [25]. In this era, identifying the advancements with specific individuals is more difficult as such identifications are often post-facto simplifications to make histories simpler and coupled with difficulty in identifying many small steps that lead to the progress seen. However, overall progress shows the continuing integration of computing into all aspects of fatigue study, from its use in modeling, controlling complex experimental test apparatus, and sophisticated sensor systems to monitor the process of fatigue.

2.3.1 Modeling/Understanding

During this period, crack formation and propagation began to be evaluated as the principal means of fatigue and its manifestation as damage, with a corresponding increase in research, resulting in rapid advancement [23, 25]. Included is a better understanding of fatigue limiting as a mechanism where loads below are insufficient to overcome certain structural barriers to allow cracks to continue to propagate [27]. Additional work led to the understanding of the crack closure phenomenon, pioneered by Elber in 1970 [22]. Microstructural work focused on the behavior of plasticity concentration zones at defects and incorporating these effects into multi-scale computational models [27]. Data analysis methods improved due to the proliferation of computing power bringing benefits to statistical analysis [11]. These are used to attempt to include multiple layered fatigue models that can better reflect micro-structural variances in presenting generalized material properties that account for the variation in flaws that occur in production.

Most research in this era focused on small crack growth and crack initiation from large crack growth where reasonably accurate models exist. Further splits into crack regimes saw small crack growth be further differentiated into initiation, microstructural short crack growth, and physically small crack growth. Greater emphasis on the multiple scientific and engineering specializations was now present in the field, with active cooperation recognized as necessary for progress. While embracing this is useful to the research, there is a persistent difficulty reconciling the diverse fields. Despite these advances, difficulties in nearly all aspects of fatigue study remain. Widely used formulas such as Palmgren-Miner and Paris are often inconsistently unconservative, restricting their usefulness [12, 22, 27].

2.3.2 Manufacturing/Regulation/Design

In certain ways, the air-force Damage Tolerance Design Handbook is a good reflection of the time's understanding of fatigue [22]. Its development was driven by the US Air Force after several failures of aircraft very early in their design lives. Notably, an F-111 wing fracture after less than 100 flying hours in another failure that is widely referenced as a milestone case that heralded a change in the field of fatigue [12, 22, 24]. The resulting Damage Tolerance Focus drastically reduced fatigue failure in air force aircraft. Regarded as an extreme step at the time, the adoption provided functional improvement across nearly all aircraft engineering touched by fatigue [12].

Damage Tolerant Design can best be summed up into two points. It is assumed that cracks are already present in the manufacturing process at all critical points. That manufacturers must prove that the aircraft will still have sufficient service life and strength/damage tolerance with these cracks present [12]. Damage tolerance was adopted to lesser degrees by nearly all aircraft certification organizations. In inspections, the intervals were fixed by the time required for the largest possible undetected crack, which would not grow to part failure before the next [11]. However, the exact precision of testing can often be variable enough that conservative margins must be observed, leaving room for improvement in the process or a change in inspection regimens altogether.

2.3.3 Experimental Testing

The introduction of computer-controlled servo-hydraulic testing machines allowed for more complex load-time histories in experimental fatigue testing. This included the development of accompanying standard load-time histories for various common fatigue parts such as ”Falstaff” for fighter aircraft or ”Hot Turbistan” for gas turbine discs Schütz [12]. Analysis of variable loading by Tatsuo Endo and M. Matsuishi led to Rainflow counting [22]. Critical gaps in accurate testing and modeling include the absence of accurate life load history of specific parts in service to assess damage levels accurately [11]. These tests have resulted in our ability to predict crack propagation improving as it has always been a more definable and narrow issue than fatigue life [12]. Additional tests focused on creating material fatigue property atlases (Boyer [28]). These atlases are often used in initial design processes for selecting materials; their use for precise predictions should be done cautiously.

Chapter 3

Production Considerations

3.1 Fatigue Sources by Production Method

The manufacturing process has a significant effect on the eventual fatigue properties of a part. The importance of this step in a part's life is because it is the time when, for the most part, the microstructural layout of the material is determined with areas of discontinuity, plasticity, and surface roughness. Those areas serve as nucleation sites that grow into cracks, leading to the fatigue failure of parts. In most cases, the production method can be characterized, to a degree, by the nature of the flaws and the number or density of these defects.

The review of the production methods focused on the fatigue performance of the various techniques to identify and elaborate on specific issues that are unique to or prevalent in the various forms of manufacture. The goal of this chapter is not to establish generalizations on the properties of these production methods but to outline issues that research has discovered and areas of interest to researchers in the aluminum production methods' effect on fatigue performance. Common among many of the articles surveyed is the trend toward developing better models that can generate more accurate estimates of the fatigue properties of the final product. Such improvements in accuracy should allow safety margins built into designs to be lowered, allowing for more efficient design from all aspects.

3.1.1 Cast Aluminum

The process of aluminum casting, while many specific methods are available, generally involves pouring molten alloy into a mold that is the shape of the final product. Two characteristics mainly distinguish the different types of casting methods; the type of mold used and how the molten alloy enters and settles in the mold. Examples of the different mold types are Diecasting, Lost-Foam, Sand, plaster, and permanent molds. Methods of pouring/injection include gravity, high pressure, low pressure, and investment. (Neff [29]).

In what will continue to be prevalent in the following sections, a current field of research is into the level of porosity in cast aluminum and its relation to the fatigue properties of the material. In trying to establish a direct relationship between micro-porosity and fatigue life, (Carpinteri et al. [30]) evaluated pressure diecast parts. This line of investigation was focused on developing a range of porosity beyond which uncertainty in fatigue life was unacceptable. They defined an equation relating porosity to likely fatigue life under cyclic loading, but they themselves describe it as only a ”rough tool” for prediction.

Additional work on porosity in cast aluminum was performed by (OSMOND et al. [31]). Focusing on micro-shrinkage pores that arise during cooling/solidification were given special emphasis in analysis to establish ”a clear link” between these defects and the fatigue life of a part. The specific parts investigated are produced by gravity die casting and lost foam casting with subsequent T7 treatment. Similar to the previously mentioned work, this was done to establish a useful level of defects beyond which a part should be rejected as too likely to fail. The defect counting was analyzed along lines established by Dr. Murakami and using an alternate [32].

With the information on porosity generated by these methods, they define a danger coefficient to relate the stress intensity factor to its threshold value for sub-critical crack propagation. They find a ”clear link” between micro-shrinkage pore size and the fatigue life, specifically in the viability of Murakami’s method of porosity analysis with the critical defect size in experimental observation bearing close relation to the value established with their approach (Glazoff et al. [33]).

Another focus of work is on mitigating the porosity of cast aluminum alloys by designing parts with casting in mind. Work by (Shukla [34]) covers in detail the ASTM standards for radiographic inspection of porosity and the method used in rating metal parts. Also covered are part design checklists. By following them, the resulting porosity of the design can be reduced by design choices such as rounded corners and wall thickness set to standard with similar corner fillets. The work was completed not as pure research but to create a helpful guide to understanding how porosity affects the aluminum pressure diecasting and how to avoid severe porosity by adhering to checklists when designing a part that is to be diecast. In a continuing investigation by (Murakami [32]), the focus was on defects and porosity in continuously cast Al-Si alloys. In his findings, the Si phase, the interface between the Silicon and the aluminum matrix, was the source of the fractures that caused the failure. Overall, cast methods will be used as a standard for comparison in many studies evaluating the fatigue performance of other manufacturing methods

3.1.2 Wrought Aluminum

Wrought aluminum has been worked into its final shape while in a solid state, as opposed to casting, where it is shaped while molten. Methods of working can include forging, rolling, and extruding. Following is a rough measure of how these various wrought methods can affect the fatigue properties of parts crafted using them.

The creation of new tools to model the impact of forging on the material properties was researched under the Air Force Research Laboratory’s Metals Affordability Initiative by

(Ball et al. [35]). It centered on using an Alcoa tool that simulates the forging and quenching process by input parameters while giving the resulting residual stress of the final part after forging. The goal was to increase further the knowledge of the residual stress that results from the forging process to establish better what effects it has on the fatigue properties of aluminum forgings. This tool, while proprietary to Alcoa, helps further the understanding of residual stress forgings that, with additional work and investigation, will eventually yield more accurate fatigue models for large, forged aluminum parts. This is part of a general trend across the manufacturing field of creating better modeling systems that improve the accuracy of design stage performance figures, according to (Veen et al. [36]).

3.1.3 Chemical Milling

The process of chemical milling or etching comes from early metal etching techniques of ancient Egypt [37]. The process involves the selective/controlled application of corrosive chemicals to metal that precisely removes the material or etches patterns into the metal. Modern techniques involve the material being cleaned, then areas not to be reduced/milled are given a protective coating to prevent the milling solution from affecting those areas. The metal is then submerged in a bath of acidic or alkaline solution, the specific solution dependent on the metal to be milled. The material is then removed at a uniform rate, with the time submerged related directly to the amount of material being removed based on the chemical solution (Bhattacharyya and Doloi [38]).

Specific analysis of the fatigue properties of this type of manufacturing method is useful as its corrosive nature can drastically affect aluminum's fatigue properties. The effect of simple chemical milling without re-finishing on low-cycle fatigue was investigated by (Spear and Ingraffea [39]). The report found, using fractographic analysis, very high magnification imaging of the material surface, that the higher porosity and pitting caused by the milling process reduced the fatigue life. This reduction in fatigue life is stated as resulting from the earlier crack -initiation resulting from the increased surface roughness caused by the chemical milling process, which is consistent with current fatigue understanding.

Using chemical milling to remove material to lighten the overall structural weight, or lightening, is more time and cost-efficient than traditional milling methods (Sesana et al. [37]). Analyzed specimens demonstrated that the only structural alterations from the chemical milling process occur on the samples' surface, with common surface roughness measurements increasing an order of magnitude. The resulting data found that the samples milled at higher temperatures had reduced fatigue strength, and the chemically milled samples' strength was lower than that of the untreated specimens.

While three sources do not clearly constitute a trend, additional evidence from the articles' own citations and surveys indicate that the resulting increase in surface roughness caused by chemical milling uniformly reduces the fatigue life of a chemically milled part in comparison to one of the same dimensions that has not undergone the milling process.

3.1.4 Additive Manufacturing Fatigue Properties

The use and development of additive manufacturing has increased dramatically in recent years. Due to certain limitations imposed by aluminum, the most important and commonly used methods are selective direct metal laser sintering, Selective Laser Melting, and Laser Powder Bed Fusion. These methods are best suited for use with aluminum alloys, all of which are in the powder bed fusion family [40].

In (Al-Maharma et al. [41]), a review of porosity effects on fatigue in all forms and specific materials on additive manufacturing, they note that the difficulty in aluminum is its high reflectivity, requiring either higher power lasers to melt the material or a slower scanning process. Given the versatility of settings available in additive manufacturing, detailed investigations into these settings effects on the material are a major focus of current research. However, most focus is on areas such as tensile strength, with a much lower volume of material existing on their effects on the fatigue properties of parts. The generally accepted fatigue understanding is based on the material's porosity, which, compared to other manufacturing methods, is more at issue with additive manufacturing due to the nature of AM, where the build takes place over a relatively long period.

In evaluating the effect different output parameters could have on the fatigue properties of the part, (Brandão et al. [42]) carried out an experimental and computational process to evaluate these effects in the powder bed fusion AM process. The research, sponsored by RUAG Space and the European Space Agency, focused on comparing various printing properties and the effect post-manufacturing surface treatments could have on the fatigue properties of the resulting part. In comparison with cast alloys, the study notes that the best-performing AM sample outperforms a comparable wrought alloy by an order of magnitude. About specimens that were milled after AM, the study showed that the most important parameter is the method of treatment after the milling, the various settings mentioned do affect fatigue, with a particular note on the effect of the contour parameter as giving much-improved fatigue lifetime in comparison to any potential surface finish or treatment.

The previous study was repeated and expanded upon in work done by (Beevers et al. [43]). They looked further into the effect the contour parameter had on the overall properties of the resulting specimen that was delivered in post-production. Quickly, the contour parameter is the outermost line in a layer that eventually forms the surface of the part, as opposed to the back-and-forth hatching style that makes up what becomes the interior of the part. They found that the contour parameter, with similar levels of minimum surface treatment, dramatically reduces the surface roughness of the material. Contour reflected the most useful setting in improving the fatigue properties of the material in comparison with the others evaluated. Interestingly, these parameters that had increased fatigue life effects were not mutually exclusive and, when combined, resulted in even greater increases in the fatigue lifetime of the material as it was tested.

Investigation into the suitability of other non-powder bed fusion-based AM techniques is also a field of interest, as they offer advantages sometimes not possible with the previously mentioned technology. One example is Wire Arc AM, which uses an aluminum wire melted via gas metal arc welding [44]. Its main advantage over laser powder bed fusion techniques is that it is more suited to building larger components by traversing more quickly and manufacturing larger layers, significantly increasing the build speed. However, the issues with porosity present in other AM techniques become partially exacerbated due to the faster process according to (Hauser et al. [45]). In evaluating the presence of pores in AM processes (Al-Maharma et al. [41]) found that the most severe effects came from irregularly shaped pores that served as fatigue crack initiation sites. In developing an analytical and computational model to more effectively link these, work done by a probabilistic model is used to represent likely defect distributions of a material (Park et al. [46]). This probabilistic approach is seen in other sources as a means of developing models to predict the microstructural effects of fatigue in a material, with AM being of greater interest as the defects are common.

Another area of interest with any new method is its regulation and creation of industry standards. The current difficulties in this are summarized well by (Mochache and Taylor [47]), where they specifically cite the example that for laser powder bed fusion processes, multiple organizations have created contradicting standards, essentially nullifying their efficacy as standards. In setting better standards, it advocates for building similar volumes of data on crack growth and other fatigue standards for the various methods of additive manufacturing that exist for different production methods to help build institutional knowledge, as well as emphasizing the development of structural health monitoring technologies as a means of addressing uncertainty with new techniques. Research by (Park et al. [46]) emphasizes that more work on standardization of regulation and the build-up of experimental and modeling knowledge is necessary to understand the fatigue life of AM parts properly.

Several of these issues can be solved through higher production rates where better knowledge of the effects and vulnerabilities of the part allows the printing scheme to be optimized, which in all evaluated cases helped reduce the porosity found in the AM parts. A primary focus of current and near-term future research is likely to be interested in the development of better quantifiable relationships between the porosity of an AM part and its resulting mechanical properties, including its fatigue properties.

3.2 Assembly and Attachment Methods by Effect on Fatigue

The intention here is to perform a quick review of assembly techniques for structural members or panels in the final system and how the method of assembly and fixing affects the fatigue performance of the system. This is often more important than the actual production method of the part as areas where two parts are joined are more difficult to model, as well as being a weakness in the system. The difficulty in conventional fusion welding and its use on the popular high-strength aluminum alloys most often used in aircraft structures led most early designs to use riveting to join two or multiple parts together [44, 48].

3.2.1 Riveting

In investigating the fatigue effects at rivet locations, (Chen et al. [49]) focused on developing a numerical approach for comparison with an experimental testing scheme. Their focus was on the crack growth and propagation phase as opposed to the crack initiation phase, with all simulations and tests having notches cut into the rivet holes with no rivets. Although their method for fatigue prediction shares the same issue with many others in that the estimations are not conservative, with the experimentally obtained values always falling beneath the predicted values. They later moved on to evaluate the effect of a rivet hole's diameter on crack propagation (Chen et al. [50]). Their findings concluded that a resulting conservative prediction gives decreasing fatigue life with increasing rivet diameter, although this does not consider the presence of a rivet, simply the hole. Riveting remains the most common coupling method when using high-strength aluminum alloys.

The use of self-piercing rivets to join thin aluminum joints is widely practiced in industry. They differ from conventional rivets in that they are not placed into a hole and then expanded; they are punched into the material where they deform the material, effectively ”stapling” the two joined pieces together. An investigation of the fatigue properties of self-piercing rivets focused on the loss of strength occurring near fatigue failure [51]. They found that the self-piercing rivets had near double the fatigue life performance of spot welds and that the SPR retained greater strength at corresponding times in their fatigue lives. Due to their simplicity, riveting and nut and bolt attachment are likely to continue in lower cost and risk applications.

3.2.2 Welding

For a long time, welding aluminum was considered difficult due to the heat effects on the area near the weld, with design preference given to methods like riveted joining [52]. This changed in the mid to late 20th century with the advent of advanced welding techniques, such as friction stir welding, of which several specific techniques exist [53]. The increased popularity of friction-stir welding as a technique for joining aluminum is a continuing trend. Its main benefit is a solid-state joining process occurring below the material melting point. In (Okada et al. [54]), the fatigue effects of such joining techniques were investigated as a standalone paper without comparison to other joining methods. In evaluating its impact on fatigue, this investigation used a combination of experimental and computational tests to assess the fatigue life of several specimens, with the concentration area being at various distances from the location of the weld, with the starter notch being perpendicular to the weld line.

In analyzing the effects of a weld line, with parallel fatigue cracks, the investigation by (Alireza et al. [55]) shows meaningful results. Their study found that using an extended finite element model considering stress residuals from the welding process could predict the fatigue crack growth along a butt weld line, a measure of progress from previous attempts at simulation. The overall understanding of welded specimens' crack propagation and fatigue effects is an area that is being improved with continuing research. Specifically, improvements in modeling such as those seen in the study above represent a reasonably accurate design evaluation method before part construction begins.

A competing form of joining, laser beam welding, is gaining traction in the market. Compared to friction stir welding, it is a more conventional fusion weld, with a laser melting the material along the joint, according to (Kashaev et al. [56]). One of its main advantages over friction stir welding is its ability to be used on parts with more complex geometries. Further comparison shows comparable fatigue crack growth performance along laser beam welded joints to the best riveting techniques. In fusion welding techniques, the benefits of welding over riveting vary, especially with the composition of the welded aluminum alloy and its heat properties in relation to fusion welding methods.

3.3 Novel Treatments to Improve Fatigue Life

3.3.1 Precipitate Alloy Training

A more novel process being investigated is the creation of alloys manipulated to alter micro-structural weaknesses. In the precipitate hardening of aluminum alloys, a widespread method for strengthening, there is no corresponding increase in fatigue, sometimes even the reverse, with the fatigue strength decreasing. In (Zhang et al. [57]), their observation of the micro-structure behavior led them to the source of this difference, where lack of precipitation along the sample edges caused the localization of damage, leading to earlier crack formation and subsequent fatigue failure. This knowledge allowed the development of a loading training scheme designed to ”heal” these areas where plasticity localization would occur. The resulting training scheme is reported as increasing fatigue lifetime to 25x its previous level. While the training procedure seems to take a somewhat long time, the applications could be very exciting if this can be scaled to an industrial process.

The training process for the under-aged samples is designed to develop the dynamic precipitation by applying the increasing external stress most compatible with the strength increment introduced by dynamic precipitation. This evolving applied training stress effectively limits the introduction of strain hardening due to dislocations [57]. This line of research represents a new approach that ”embraces” dynamic loading by using it to effectively “heal” the structural weaknesses of the material. While this specific technique is best suited to precipitate strengthened alloys, the underlying philosophy could find valuable applications elsewhere.

Chapter 4

Fatigue Inspection and Monitoring

In addressing the issue of fatigue failure, inspection and monitoring during the system service-life of a system were the first and most essential means of ensuring safety. The ability to detect defects' number, location, and size remains important after manufacturing throughout the system's service life. However, many analysis methods used for quality control during manufacturing previously mentioned in Chapter 3 require that the material or part be destroyed, preventing their use on operational systems. Systems that detect flaws as early as possible during inspections are essential to ensuring system safety, resulting in continued research interest. These inspection techniques can be grouped into the field of Non-Destructive Evaluation. Separate from scheduled inspections, the practice of health monitoring or continuous monitoring of the condition and behavior of parts during operation is gaining increased interest for two overarching reasons. The first addresses inspections by aiming to develop the ability to detect structural damage by changes in sensor readings, reducing or eliminating the need to take the system out of service to perform inspections. The second is that it promises to resolve a significant source of uncertainty in fatigue models stemming from inaccurate or generalized service stress histories.

4.1 Material Inspection Methods

Methods of material inspection by nondestructive evaluation, NDE, vary considerably in their means, utilizing mechanical, electrical, thermal, and radiological mechanisms to detect discontinuities. In understanding these methods, it's important to emphasize that inspections are a required nuisance interrupting profitable operations, so any reduction in the time required is significant. With this view, research into NDE methods focus on how new developments affect the rate of inspection, accessibility, or probability of detection. Technique accessibility is influenced by what is required to conduct the inspection, such as operator training, workload, and equipment. The probability of detection is the governing limitation of this practice, statistically defining the method's reliability as detecting a crack/discontinuity of a specific size [58]. This limitation is critical given the importance of crack size in determining remaining service life and directly affects the required frequency of inspections. In the following brief survey of techniques, the techniques of NDT that cannot be used on aluminum, such as magnetic particle testing, were avoided.

4.1.1 Visual Inspection Techniques

Visual Inspection has the longest historical use due to its evident simplicity, but continuous improvements have kept it relevant. The earliest formal improvement in crack inspection was with the first use of the carbon black rubbed onto clay pots to highlight cracks, later by dipping trail axles/wheels into oil, then rubbing with chalk to bring the oil out of the cracks, revealing them. This method is also the most widespread due to its simplicity and low associated costs [58]. The use of a liquid dye penetrant to enhance the visibility of defects has a long precedent, and its use is continued today. The penetrant works due to capillary action drawing the liquid into the cracks, where after a wipe-down of the surface, the remaining liquid marks the cracks with importance placed on contrast. In pursuit of higher contrast, red dye is commonly used, and later the creation of fluorescent dye for use with certain types of light further increased defect visibility. This method can detect any size surface defect when paired with an optical or electron microscope, with the smallest detectable defect rating the accuracy of the specific inspection regime. The method for recording these defects to generate a meaningful categorization standard is laid out in ASTM E165. Visual inspection with or without liquid penetrant is the most used method of inspection due to its speed and ease, meaning it is likely never to be surpassed in this.

4.1.2 Eddy Current

Eddy current inspection works by sending an alternating current through a coil to generate an electromagnetic field, which, when placed near the conductive item under test, will induce eddy currents in the material. Cracks or flaws present in the material will cause distortions in the eddy current, which will be detected by a detector in the tool, revealing the location of the flaw [58]. Refinement of Eddy current testing techniques continues with research focusing on developing more sensitive test apparatuses and better processing techniques, such as SQUID magnetometers, developed by (Ma and Wikswo [59]), that focused on low-frequency methods for detecting defects further below the surface. Eddy current analysis remains a popular technique due to its simplicity and well-developed automatic detection and post-processing programs that allow detection of sub-surface defects.

4.1.3 Thermography

In thermal-based NDT, the focus is on the temperature of the surface, which is recorded either by temperature-sensitive coatings, individual sensors, or the most common method; Infrared imaging/thermography [58]. The other key consideration regarding thermography is whether the target specimen is heated and how it is heated. The two important characteristics of heating are whether the heat is continuous or pulsed; and how it is generated. The methods of heat generation in common use include heat lamps, blankets, laser/microwave excitation, heat guns, and induction by eddy currents [60]. An investigation by (Usamentiaga et al. [60]), focused on the detection of fatigue cracks in chemically milled 737 fuselage panels with AC-induced infrared thermography. This research was carried out with a direct investigation of the exact type of cracks responsible for the fatigue failures found in [61]. They aimed to reduce the time and costs of the mandated inspections ordered by the FAA as a result of the multiple in-flight fuselage panel removals. Commonly, some form of post-processing is applied to the data to emphasize further or distinguish the areas where discontinuities/temperature anomalies are, such as the processing based on the skewness parameter investigated in (Madruga et al. [62]). This type of research, as well as thermography often being able to inspect large areas very quickly, keep it a focus in NDE.

4.1.4 Ultrasonic

Another Nondestructive testing method is ultrasonic inspection, where high-frequency vibrations are induced into a material. When these vibrations reach a discontinuity, they are reflected or scattered, and the reflections are analyzed. This method has several drawbacks, most notably its difficulty working with irregular/complex shaped parts and its usual requirement of a fluid interface between the apparatus and the part, which is usually some form of gel. Another difficulty is that this method requires a more skilled operator than those previously mentioned [58].

Investigations into more advanced ultrasonic fatigue crack detection techniques continue today, especially regarding return analysis methods. Development of specific note includes laser-induced thermal stress-induced crack closure, resulting in altered scattering of the ultrasonic waves, making the defect more noticeable (Nagy et al. [63]). Due to the high thermal diffusivity in aluminum, this crack closure method can be particularly effective with lower power. This specific technique is very infrastructure dependent; further miniaturization of high-power laser technology is needed for portable inspection to improve accessibility. However, as a whole ultrasonic investigation is a useful tool, especially if normal reading are established prior to the presence of defects.

4.1.5 Radiography

The core principles of radiographic nondestructive inspection have little functional differences from the x-rays or CT scans at a hospital. The use of penetrating rays, either x-ray, gamma, or neutron, applied to the inspected article, with the shadows or patterns cast on digital imaging plates being analyzed [58]. The transition from film-based radiography, which required technician analysis, to digital has allowed this method to be less subjective and more uniform as computer-aided analysis improved the uniformity of analysis [64].In their investigation (Wang et al. [64]), they developed post-process analysis techniques to automate crack detection and minimize the time required to inspect aircraft parts.

Digital radiography has also seen widespread adoption to analyze and model the porosity of different aluminum alloys under different production methods with heavy use of computational tomography (Senck et al. [65]). The use of computational tomography, CT scans colloquially, has helped generate three-dimensional renderings of the porosity in aluminum material samples, with these detailed scans giving direct data on the amount and size of discontinuities, which can be used for developing models of use in modeling the materials fatigue life [65]. Main concerns in accessibility are radiation risks, which skew the development of these systems towards non-portable automated infrastructure to prevent personnel exposure.

4.2 Structural Health Monitoring

The miniaturization of sensors and computers has allowed for a new approach to be applied to the issue of fatigue with the installation and use of health monitoring systems. Nondestructive evaluation techniques are very well suited to the discovery of damage in localized areas; however, without a solid indication of where the damage is, surveying whole systems is a time-consuming process. The development of systems that can detect damage system-wide is where much research has focused in the past few decades [66]. In defining the function of a structural health monitoring system, (Rytter [67]) defined a five-step series of questions the system should address; the existence, location, type, extent of any damage and a prognosis of remaining life. In developing this information, SHM systems rely on models that use as detailed a record of the operational loads experienced as the system allows to improve predictions. This eliminates one of the sources of uncertainty in prediction due to inaccurate service load data by recording that data in as much detail as possible, improving over previous notional mission loads. As with operational load monitoring, the crack growth can be modeled more accurately, allowing for narrower safety margins and greater lifetime.

The main driver behind this research is to reduce or eliminate time-based maintenance, where maintenance/inspections intervals are scheduled by the operating hours of the system according to damage tolerance design, in favor of condition-based maintenance, where the maintenance/inspection occur once the systems identify a deficiency or failure through structural health monitoring with the objective being to increase utilization and reduce maintenance costs [68]. Early adoption by militaries whose aircraft experience varying load histories increases the benefit of SHM, while economic barriers, such as cost, are a lower priority than aircraft availability and performance. Additionally, their aircraft experience greater variations in load history, especially combat aircraft, compared to commercial aircraft, by (Branco and Bussamra [69]).

4.2.1 Method of Sensing

The challenges of structural health monitoring have necessitated the development of newer Non-Destructive evaluation methods. The need for sensors that deliver real-time, compact, and cost-effective information is incompatible with legacy NDT which are more suited to periodic inspection. Differing from NDE methods, which are focused on detecting damage, the need for continuous operational load monitoring, OLM, is needed to create detailed load histories. Also important are models that use these measurements at specific locations to extrapolate values at critical locations where fatigue is likely to be an issue.

Impedance-Based Methods

One of the critical benefits of impedance monitoring is its ability to function on complex structures with much greater simplicity than other methods of comparable detection capacity. While it is not as helpful in building a loading history, it is very adept in detecting damage. This method of detection is comparatively advanced, receiving a great deal of interest due to; its low cost, specific detection of most types of damage, function on multiple materials, ability to monitor large parts, and simplicity, according to (Le et al. [70]). Impedance sensors work by analyzing the impedance response of a piezoelectric transducer mounted on a structure subjected to ultrasonic vibrations. Any change from a baseline would indicate a change in the structure, usually indicating damage [71].

In developing a method to better identify damage, methods used by (Rabelo et al. [72]) involved testing the sensors under fatigue conditions while detecting cracks by other means. It then correlated the resulting impedance data with the crack detection data to associate the impedance reading with the crack size. This is the main work of structural health monitoring the statistical pattern recognition from a sensor of values associated with damage. In facilitating this recognition, post-processing is applied to the data by integrated impedance analyzers to filter out noise by (Gollnick et al. [73]).

In addition to impedance-based sensing with piezoelectrics, work done by (Martin [74]), made use of the same piezoelectrics to generate electrical energy from normal operating vibrations and oscillations occurring in the structure, which then powered the sensing and transmission of data to a SHM system. Being self-powered and wireless removes the need for wiring for power supply and data connection, simplifying the system significantly. In addition to generating power, the piezoelectric serves as a sensor and actuator, with the impedance detected by the sensor being analyzed compared to a known undamaged baseline, with differences indicating damage occurred. The wide application of impedance-based sensors with remote monitoring is likely to be an important enabling technology in health monitoring applications.

Strain Monitoring

The integration of sensors into composite patch repairs is investigated by (Lee et al. [75]). The specific method of monitoring is with transmission-type extrinsic Fabry-Perot interferometric sensors that detect strain magnitude and direction through the loss of light intensity that occurs when the gauge is strained, with similar basic principles to electrical strain gauges. When embedded in a patch on the likely crack growth path, these sensors will see strain spikes as the crack reaches the sensor and give notification of total patch failure or loss, a crucial alert when the repair is on a critical structure. They can be used in place of more conventional strain gauges, the main benefit being lower power usage [75]. The use of traditional strain gauges for operational load monitoring was evaluated by (Namura et al. [76]), with specific emphasis on processing the data with a Kalman filter to give better representation with a lower rate of readings.

The importance of strain readings for operational load monitoring, OLM, is stressed by (Steinweg and Hornung [77]). In their research, it was necessary for the required level of confidence to meet regulatory assurance standards against failure. That, without the operational load monitoring, the ability of the system to reliably predict future failures would not satisfy airworthiness standards. This would negatively impact the utility of the system in addressing the much higher safety standards demanded by national aviation authorities.

Stress/Strain Reconstruction

To make structural health monitoring more effective by increasing the amount of a structure that a sensor can generate useful data over and therefore reducing the required number of sensors is an essential aspect of existing research. The use of computer modeling has been explored as a means of generating/extrapolating strain values along an entire part or structure based on a limited number of measurements. Research by (Namura et al. [76]), evaluated the use of a single strain sensor, with its measurements being plugged into a simple finite element model, to generate the likely stresses at 74 critical points along the blade of a wind turbine. In this method, an increase in the number of strain gauges only ever resulted in increased modeling accuracy. The system, with data available from only one sensor, produced values with an averaged error below seven percent. With these values extrapolated, their input into models to determine the damage is the next important bit. More complicated finite element models are possible, with the level of complexity being limited by the system's computing power to complete the modeling for every measurement set [78].

4.2.2 Data Processing, Analysis and Prediction

With the increased availability of data stemming from the implementation of structural health monitoring systems, investigations into potential uses for that data are a growing interest, especially with advances in computer science and engineering. Ever-present difficulties in devising consistently reliable analytical models for predicting fatigue life have led to computational methods being given increasing independent influence on model development. Consistent improvement in the reliability and accuracy of these damage detection and fatigue failure prediction models has been shown, especially as advances in computer technology allow larger amounts of data to be collected and increased processing power enabling more complex and accurate models to use the greater volume of data [66].

Although a significant driver of SHM research is the potential of reducing required NDE-based inspection across large fleets, early data collection is likely to benefit from increased rate and thoroughness in NDE inspections. During early training, increased accuracy and frequency of damage assessment that includes location, size, and type of damage, the less uncertainty in fatigue lifetime and damage prediction will be [66, 79]. Improvement in this area is especially critical in narrowing the resulting probability distribution in predicted remaining fatigue life, according to (Gobbato et al. [80]). The fatigue damage probability models in several studies also showed reduced standard deviations and more accurate median points in both recursive learning applied to a single test component and across a fleet due to better separate damage data in training [79, 80].

In SHM systems, data management requirements often limit the frequency of measurements to orders of magnitude less than the sensor's capabilities, so processes have been developed to represent complex load monitoring data into a more compact format. This post-processing of the sensor readings allows a more accurate representation of the experienced loads than could be represented by un-processed pure frequency-based sensor sampling in the same amount of storage space. The method used for processing can be signal-based, such as Kalman filtering, or it can be tailored towards the data's use in fatigue calculations [76]. Such as fitting the recorded signal into a simple cyclic loading scheme via Rainflow counting and storing the relevant coefficients [78]. A simple damage evaluation system can further reduce this by constructed loading with corresponding hysteresis cycle counts and S-N curves to record damage accumulation via Palmgren-Miner's rule. This process works for a single critical point and would have to be done for all points of likely stress concentration at increased risk for fatigue damage.

Similar improvements in the accuracy of other models could be made by applying more-complex data-driven methods to other fatigue-related equations. Work by (Neerrukatti et al. [81]) showed a hybrid approach where data-driven learning is used to adapt existing physics-based models of fatigue crack growth and fatigue life to better match the monitored system. This is done by using data from similar experiments and analytical methods as a base of knowledge to initially fit the coefficients, such as stress intensity factor, better reflecting the experimental properties of the part better.

By repeating the regression to develop new coefficients as new data is added, the model increases in accuracy. However, while this process by regression allows a more accurate model coefficient fitting, by fitting only a linear-elastic fracture-based equation, it suffers from greater inaccuracy in regimes where those mechanics perform poorly. The development and widespread investigation of machine learning and neural networks have led to models that can avoid traditional analytical methods for fatigue damage and crack growth calculation, likely resolving the shortcoming as mentioned earlier of the regression-based model [81]. These methods use large amounts of sensor data as input and custom statistical/probability/learning-based processes to define relationships between monitor information, fatigue damage, and remaining structural life. However, a middle ground between these data-driven learning and physical analytics-based approaches is a field of focus, as a system that combines these approaches tends to produce more accurate predictions than separately. This synergy is found by (Chen and Liu [82]), where neural networks could apply a greater number of fatigue influencing factors, outside of commonly used stresses and strains, to perform fatigue data-fitting to a self-made physics-based regression model that used several fatigue life stress and strain equations.

Their "Probabilistic Physics guided Neural Network" better matched experimental data than its constituent physics-based, and neural network elements could separately [82]. The use of supervised learning to develop neural networks shows promising viability in their results, especially in matching experimental data at better levels of accuracy than existing analytical models [66]. These data-driven methods, in combination with the current physical models, are very promising in adapting physics models that are by nature inferred from experimental data for most materials to model in-service parts better while also accounting for the statistical variation in the quality of the parts that ultimately makes fatigue life most challenging to predict.

Chapter 5

Crack Growth Mitigation and Repair

The earlier detection of fatigue damage provided by systems mentioned in Chapter 4 is immediately beneficial in determining if a part must be replaced or repairs must be made to the system. Structural and material repairs allow for the correction or mitigation of any issues that fatigue modeling could not anticipate. This ensures existing systems can remain in service, a desirable outcome for the operator from an economic or strategic standpoint. Given the uncertainty in fatigue lifetime understanding and predictions, even with its decrease over the past two centuries, effective repair techniques are extensively researched. The effect of various repair techniques on fatigue constitutes a large volume of existing scholarly work on fatigue management.

In their text, (Adams et al. [83]), emphasized that the repair that “should” be completed depends less on the best solution but on the repair that can be achieved with the available tools and skilled labor with consideration of time constraints. However, subsequent sections will focus more on the fatigue life benefits of repair techniques with only brief mentions of labor and time constraints.

5.1 Bonded Patch/Reinforcement Repair

A patch repair, where a ”patch” of material is placed over a defect, is conceptually and in practice quite simple. The addition of the patch allows a portion of the loads to be transferred across the patch, resulting in a lower local stress/load occurring at the location of the defect. In recent years, significant improvements in the ability to model the effects of a patch repair on the fatigue life of the system have been made. The quantification of the benefits of the patch has allowed more rigorous study into the benefits of different patch materials, with much of this focused on improved composites. Along with patch materials, the method used to attach or ”bond” the patch with/on the part can be done using a number of methods; adhesive, welding, riveting, or molecular bonding process. However, the bonding process adds a unique mode of failure, debonding. This occurs when the method of bonding fails partially or wholly, leading to reduced strength or the patch no longer remaining in place. Of available patch repair methods, composite material patches are the most widely used, especially considering their greater ease in application [83].

5.1.1 Composite Patch

The performance of a composite patch can be influenced by many factors, including the mechanical and geometrical properties of the patch and its material, the nature of the loading at the application site, and the performance of the adhesive used, complicating fatigue analysis. Additionally, [83] notes their specific utility in the aerospace sector due to high performance for their weight and low profile, where they can be removed and replaced if needed. These properties have made the investigation of composite repair a field of continuing interest. It can be roughly defined as investigations into improved analytical/computational modeling to better quantify their performance and new patching techniques and materials to enhance their performance.

Recent investigations have tended more towards the computer modeling aspect of investigation and increasing the accuracy of the same, according to (Cui et al. [84]). The motivation behind this shift is similar to the driving force behind the same changes in other areas of engineering: the ability to rapidly evaluate multiple design options, cost savings compared to multiple physical experimental models and tests, and the desired ability to accurately predict fatigue life in more complex structures.

Before venturing into areas of conflict over means of simulation, the more common techniques should be explained. In surveyed articles, nearly all were based on finite element methods, with differing meshes but divided into three distinct parts: the component, the adhesive, and the patch. An observed commonality was the tendency to design the specimen under consideration to one of several standards, such as the compact tension or centrally cracked plate, to allow better comparison with previous investigations or concurrent experimentation for verification. The programs began to diverge and continued to evolve in several areas: method of crack growth simulation, if and how debonding effects are included, and the position of the cracking. Concern over prediction accuracy has been continuous in all aspects of fatigue study, with composite repairs affected as well.

A pervasive issue in fatigue life predictions can be usefully depicted by Figure 5.1 (Yousefi et al. [85]). Their modeling method utilizing Abaqus, with its basis in strain analysis of Hysteresis-Loops, overestimated the fatigue life inconsistently. With this, their model could discern that the repairs result in fatigue life improvement, but only as a generality, with their quantification being inconsistently un-conservative.

The neglect of de-bonding in a model will have effects, especially when debonding occurs, which was commented upon by (Schubbe and Mall [86]). Their findings do help establish the more general trend that absent significant environmental factors, laminate debonding requires significant crack growth in the component for damage to occur to the patch. The most influential contributing factor in patch debonding is corrosion of the adhesive. An investigation into salt-water vapor exposure on repairs, carried out by (Kam et al. [87]), found that fatigue life was significantly degraded by the exposure. While not able to specifically attribute the failure to the adhesives, the article does eliminate the other likely sources

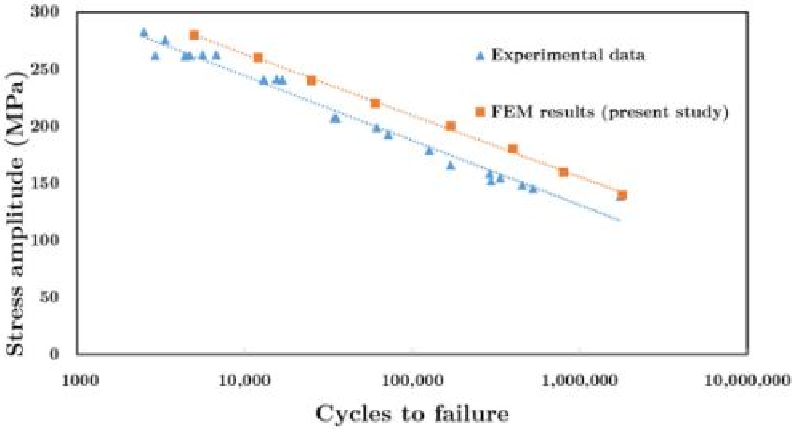


Figure 5.1: ”Stress amplitude versus cycles for undamaged aluminum 6061-T6 for both FEM in the present study and experimental data” from (Yousefi et al., p.7), CC4.0 (http://creativecommons.org/licenses/by/4.0/)

of rust and delamination as well as the specific “corrosion fatigue” mechanism. However, it is pointed out that corrosion-resistant adhesives are an active area of development that generates reasonable improvements.

In evaluating the geometry and orientation of the patch and how that influences the fatigue life of the repair (Kam et al. [87]) determined that, regarding patch dimensions, the thickness has the greatest influence on the fatigue life post-repair. This is eminently reasonable given the reduced stress experienced by a structure under the same loading with a greater area. Their improved quantification of this relationship is helpful in selecting specific patches to be used in repair. Additionally, they defined for a graphite epoxy patch the optimization of the thickness for single-side application and application to both sides of a plate or other thin aluminum structure. Mass gain is defined in research as the relative difference between the thickness of the single-sided and double-sided patch needed to maintain the same stress intensity factor at the crack tip, (Albedah et al. [88]),. The findings of the aforementioned study supported the use of double-sided composite repairs as requiring less mass for the same improvement, with the degree of improvement in fatigue life largely dependent on the shear modulus of the adhesive. With centrally cracked plates being a theme of previously mentioned research, the evaluation of repairs along material edges was explored by (You et al. [89]), where a modified system of stress intensity factors was developed to increase the accuracy of fatigue life prediction in off-center cracks with repairs. However, as in other surveyed studies, they suggest that the investigation would benefit from better modeling of the patch. Separate from the geometrical properties of patches discussed above, the research and quantification of experimental fatigue data for patches of different composite material is essential as new materials continue to be developed. Graphite-epoxy and Boron-epoxy, two of the most widely used composite patches, were investigated by (Abdelmadjid et al. [90]) to establish that for a variety of load ratios, composite patches increased cycles to failure by

Further development of patch repairs includes the introduction of ”smart” patches that include sensors to monitor the repair. As mentioned in section 4.2.1, embedding sensors into the patch has several benefits over a standard patch [91]. These sensors observe a critical area where cracking has already occurred and is likely to re-occur. This simplifies observation under a patch, a self-evidently vital area to monitor that otherwise would require the patch be removed or other means of inspection brought in. This also mitigates the risk of loss of strength from debonding, as lower than expected strain values would serve as an early indicator of failure [75].

5.1.2 Aluminum/Metal Patch

As a result of the difficulty in adhesively bonding aluminum patches and partially to their benefit, other methods are necessary for attachment. For decades, aluminum patches have had problems in achieving comparable performance to composite patches for several reasons: difficulty in shaping reinforcement for non-flat surfaces and unsuitable attachment methods. Previous investigations into the performance of aluminum patching where the bonding mechanism was welding or by bolt and nut emphasized the creation of new areas of weakness along the weld lines that are by the nature of a patch already close to damage (Cui et al. [84]). The development of different methods of attachment was necessary for this method of repair to compete with composite patches.

The investigation of solid-state diffusion bonding, where under heat and pressure, two components' atomic migration occurs across the interface between components resulting in homogeneous micro-structures across the bond (Chaturvedi [52]). The knowledge base in this field exists as diffusion bonding is commonly used in producing high-performance aerospace components. Previous Specific investigations into diffusion, as a means of patch bonding by (Dehghanpour et al. [92]), found it feasible with comparable economic and strength performance as composite patches. Compared with adhesively bonded patches, the benefits of diffusion are the near practical inseparability of the component and patch and equal expansion coefficients together render debonding a practical non-issue. The research on this was limited to the ultimate strength of the part after the repair, with no fatigue testing. However, the paucity of information on the fatigue performance of this method of bonding compared other methods, renders this a more uncertain prospect but useful area for future research.

5.1.3 Reinforcement before repair

The methods mentioned in 5.1 can also be used for structural reinforcement before the presence of cracking. This would mean that spots identified as likely to suffer fatigue damage could have patches applied to delay the onset of damage, as the application of a patch before crack formation, in general, will result in greater life extension compared with patches applied after Boscolo et al. [93]. For the methods of repair mentioned in subsequent sections, apart from surface renewal, such action will not be possible as they require the presence of cracking to have meaningful effect on the system.

5.2 Welding and Additive Repairs

The increased use of Additive Manufacturing in production has led to investigations into its use for crack repair. One of the resulting methods is known as Additive Friction Stir Deposition. The use of friction stir welding rather than fusion welding is for the same reason stated in 3.1.4, to avoid expansion cracking and material strength loss in the area affected by the heat [94]. The benefits of friction stir welding combined with deposition, as opposed to other additive manufactured repairs, include the mixing between the deposited material and the material of the part caused by the stirring process. This technique developed as an evolution of the friction stir welding process.

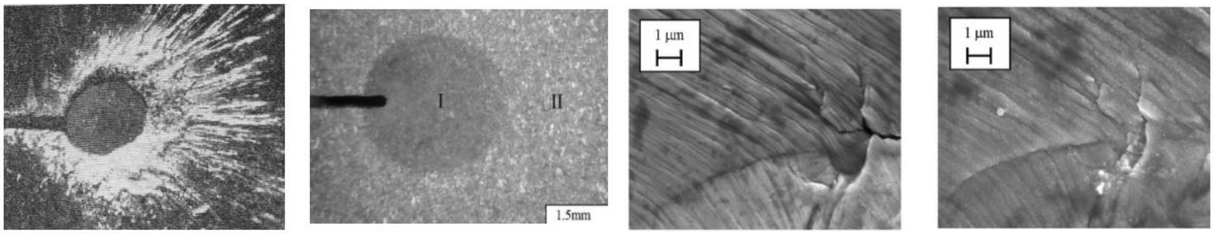
The use of welding techniques to repair cracks is well-established in existing practice. Conventional welding techniques such as arc welding and other fusion welding methods are less useful in aluminum repair for the reasons mentioned in the previous paragraph. Work done by (Tweedy et al. [95]) found that conducting friction stir welding along a crack site effectively removes the crack. While the report had no analysis on the subsequent fatigue life after repair, it found that the repair was sufficient such that a part incapable of service due to fatigue cracking could continue in service with shear strength comparable to newly manufactured values. Similar work on this process of repair by (Wang et al. [96]) focused on the parameters used by the friction stir welding process and how they would affect the fatigue performance of the repair. Their findings indicated that the fatigue life of the crack repair was sensitive to the FSW parameters, specifically advancing speed and rotation speed, with middling values being identified as the best for fatigue performance. The early failures of the poorly optimized parameter settings were due to delamination between the repaired area and the rest of the part; however, this still occurred after the unrepaired specimen would have failed.

Later work on additive deposition in combination with the friction stir welding process was completed by (Joey Griffiths et al. [97]). While no experimental or modeling data was collected on fatigue in this research, it paved the way for work done by (Peter Martin et al. [98]) on aluminum 6061 with a similar process. Their use was evaluated solely in an experimental manner typical of weld repairs where the crack had been machined out, leaving behind a groove that is then covered by the weld/AM process. Their tests were conducted on uncracked specimens with no loading history that had a groove machined in. Still, their results indicated that the fatigue life with the repair was better than the specimens without the repair. An area of further research would be the use of this method on sites that had experience fatigue damage to allow for evaluation of the fatigue performance with a previous load history and associated fatigue cracking rather than just the repair. This would enable a better understanding of what fatigue life extension such repairs could grant, allowing some comparison with similar studies on other repair methods.

5.3 Surface Treatments

The use of surface treatments as a means of retarding fatigue growth works by removing surface defects and roughness to prevent crack nucleation or remove existing micro-cracking. These treatments most effectively address corrosion fatigue, where crack initiation is most likely to occur on the surface. The use of polishing or grinding of some form to get rid of surface corrosion is a process that predates any knowledge of fatigue but is nevertheless effective. In experiments undertaken by (Arcari et al. [99]), the removal of the surface material yielded improvements in fatigue life in all evaluated cases. Significant effects were observed in crack initiation, with modest effects on fatigue crack growth attributed to the removal of micro-cracks preventing joining. The fatigue benefits above occurred outside of a corrosive environment as evaluating the benefit of surface removal in corrosive environments was found to be very difficult to determine experimentally, where the time scales of environmental effects and high-frequency test procedures on servo-hydraulic machines are significantly different.

To avoid this uncertainty in situations where removal would result in degraded corrosion resistance, other surface treatments that preserve these properties can be more reliable. In work done by (Mohin et al. [100]), a fatigue cracked aluminum plate was exposed to a pulsed electromagnetic field. The field induces current in the plate, which is much stronger at the location of the crack and can cause crack tip blunting and healing. The effect on cracks of the treatment can be seen in Figure 5.2.



(a) Crack-tip Closure (b) Tip State Change (c) Crack pre-EMT (d) Crack post-EMT

Figure 5.2: ”Effect of Electromagnetic Field Treatment” from (Mohin et al., p.2), Creative Commons 4.0, (http://creativecommons.org/licenses/by/4.0/)

The effects of the treatment were beneficial, with fatigue cycles to failure uniformly increased over untreated specimens. However, they were unable to establish a clear correlation between the intensity and number of treatments with the degree of fatigue lifetime performance. Investigating this would better determine how effective this technique is as a repair. Some drawbacks to this treatment cannot be done in situ as the required intensity of the electromagnetic field to generate these effects would damage any electronic components. The effect is the part must be able to be removed entirely or isolated before the repair can be done, which limits the scope of applications of this method of repair.

5.4 Crack-stop Hole Procedure

The crack-stop hole is the most common method of crack repair in current practice [101]. The process is to drill a hole into the material at the crack tip. The created “stophole” reduces the stress concentration at the crack tip, effectively arresting crack growth. This is due to the hole requiring the crack to go through the initiation process again. Existing research findings focus on the fatigue life effects of the hole’s geometry and treatments that can be applied to the hole to further slow growth.

In investigating the improvement in the fatigue life of a sample specimen undergoing this procedure, (Song and Shieh [102]) evaluated the effect stophole diameter had on fatigue life. They found that increasing the diameter of the stophole resulted in corresponding increases in the fatigue life of the 6061-T651 specimen. The tests were carried out under a uniaxial loading mode with compact tension specimens. This result was further reinforced by (Ayatollahi et al. [103]), who developed a finite element model to evaluate identical specimens for the same hole diameter. Their modeling reaches the same conclusion. However, a more direct comparison in results is prevented by slight differences in their setups, namely the location of the stophole and the depth of the notch at initiation. Expanding on their use of a FEM, by integrating with crack initiation and growth models. The specific equations used in the model are the NASGRO crack growth equation, and Morrow mean stress effect [103]. These are linked to commercial ANSYS FEM software to supply the stresses used by the models to run the simulation.

Moreover, both sources observe that fatigue life extension comes entirely from the additional cycles required for crack re-initiation on the far side of the stop hole. Further, in evaluating the total fatigue life of the specimens with stopholes, the time spent in the crack-growth phase varied less than 2 percent for the chosen stophole diameters [102]. This specific action is why stopholes are best described as crack-growth arrestors rather than retarders because it is merely a ”pause” in crack growth rather than slowing it. Moving on from research done in verifying that the general method is sound, strategies to improve the technique by using multiple stopholes of varying size, hole shapes optimized for delayed crack-initiation, or reinforcing the edge of the hole, sustain interest in the area.

In improving the performance of stopholes by strengthening, (Bahloul et al. [104]) evaluated applying the interference fit method, initially developed for slowing crack-initiation at fastener holes. The interference fit is a process where a bushing is inserted into the stophole and then expanded, which induces ”beneficial residual stresses around the hole edge.” The size of the interference fit, the change in radius of the stophole caused by the expansion, was shown to have a very pronounced effect on the fatigue life of the Single Edge Notch Tension specimen. It finds that the best fatigue life extension occurs in the setup that induces the highest compressive residual stress on the hole edge and outlines a process that is to be used to develop the best interference fit for different test/design scenarios [105].

Similar experimentation by (Takahashi [106]) into inserting adaptive wedge members into stopholes, designed to place continuous stress on the hole edge even after crack re-initiation, is ongoing. The concept shows exceptional performance, but for practical use, the adaptive tightening mechanism that consists of tensioned wires, springs, pulleys, and counterweights would need considerable alteration or miniaturization for installation on a repaired system. However, this method is an improvement compared to the previously mentioned systems as it would also retard crack growth after initiation.

5.5 Combined Method Application

Minimal research material is available on the combination of two or several techniques mentioned in this chapter, which is a notable gap in existing scholarly work. One such example of the utility of this type of thinking is found by (Bachir Bouiadjra et al. [107]). Their investigation showed that after crack formation, the application of an overload significantly retarded crack growth, resulting in life fatigue life increase. This “overloading” should not be confused with the century-old, since disproven fatigue theory, but is just the application of a single extremely high amplitude load compared with the rest of the loading regime. However, it also showed that applying a carbon/epoxy patch immediately after the overloading resulted in fatigue life improvement of 2 orders of magnitude [107]. This observed effect is entirely order dependent, with the application of the patch before overload found to attenuate the process’ effects, resulting in comparable improvement to sole patch application rather than orders of magnitude mentioned earlier. However, further investigation is needed to verify the magnitude of the benefit or the range of potential targets for this process through computational modeling of the effect or broader experimentation.

The combined application of CFRP laminate patches and crack stopholes was evaluated by (Vutkuru [108]). The modeling and experimental results indicated that the reduction in stress by the CFRP patch further reduced the stress on the edge of the stophole, increasing the fatigue life of the model by delaying crack initiation on the hole edge. The same synergistic effects were observed between crack stopholes and glass fiber-reinforced epoxy patches [109].

While two examples are useful, the justification behind this area of research is that many repair techniques have separate methods of action, which, if combined, will likely have synergistic effects that outweigh potential modes of interference between them. This can be easily justified between approaches focusing on alterations at crack locations and bridging/patch repairs that reduce stress and strain at crack locations. The dearth of investigation into these combinations, specifically with composite patches and crack stopholes or weld/AM repairs, is interesting as combining these techniques would likely result in improvements with minimal additional cost or effort.

Chapter 6

Conclusions

6.1 History/General

In many cases, a direct link between a fatigue-related failure incidence and subsequent research can be established, as interest has driven funding toward the field to find and solve the problem that caused the failure. This was evident in the train axle failures of the 19th century, the systemic aviation failures like the Comet and B-52s in the fifties, and still today with incidents like the panel removal on Boeing 737s of recent years. Despite this, the reduction in total or catastrophic failure due to fatigue is a sure measure that research and regulation are producing very tangible benefits and that this trend is likely to continue. Additionally, two relatively distinct mindsets and motivations can be seen in the history of research into fatigue. One is in research dedicated to better understanding the process and science of fatigue. Alongside this is research to better compensate for lack of understanding or to solve specific design issues. These two areas complement each other in their coverage of the issues and will likely remain a distinct pattern of research in this field of study for years to come.

6.2 Manufacturing

In evaluating fatigue research based on the various methods of manufacture, there are several common threads of research between them that are the focus today. One is the focus on developing and modifying existing production methods to mitigate the porosity of the resulting material after that are interests in creating better and more accurate computational models and measurement methods that can more directly relate the material's porosity to its fatigue lifetime. In new fields of manufacturing, primarily additive manufacturing, research continues along similar lines to other manufacturing methods, especially the development of models linking material porosity to fatigue lifetime. It also extends to areas previously tread by other methods, specifically the build-up of institutional experimental data to better predict operational fatigue in terms similar to legacy manufacturing techniques' methods of fatigue life and damage tolerance.

In evaluating methods of joining different parts, the lack of practical, direct comparison between various welding and riveting techniques seems a confusing oversight. This sort of research or guide would be beneficial as one goes through the detailed design process of any engineered system, but it appears to need more in the available body of knowledge. Additional studies attempting to create direct methods of comparison between the different methods of part joining would be a valuable area of expansion in the existing literature in this field.

6.3 Fatigue Detection and Monitoring

Sustained research and development in damage detection methods has dramatically improved with the increasing miniaturization of computer technology. This can be seen in systems that conduct scheduled inspections and others that monitor operations constantly. In inspection-based detection, current areas of focus in NDE techniques trend towards faster inspections, better detection acuity, and reduced workload through increased automation. In SHM, sensor development continues in miniaturization, cost reduction, and better data processing to improve detection and further adapt NDE practices to the needs of structural health monitoring systems.

Increases in the accuracy of damage detection and remaining useful fatigue life estimates by structural health monitoring systems will advance the trend toward their more widespread adoption to allow condition-based structural inspection and maintenance. Future aspects of SHM likely to see increased research include improved training data collection, better computation allowing for more detailed load condition construction from limited sensor data, and more frequent sampling to increase the accuracy of any data-driven modeling. Further research will likely continue into the combination of data-driven modeling and the use of neural networks to adapt physics-based models to more complex features and structures with increased accuracy. Indeed, the main limitations in the utility of SHM are likely to remain available computing power, data storage, transmission, and miniaturization in both the sensors and computer processing.

6.4 Repair and Maintenance

In the existing literature on repair, especially from a historical perspective, the development of repair techniques has often been a reaction to the uncertainty existing in predicting the fatigue lifetime of systems and the need to compensate for such inaccuracy. In evaluating future research in this area, several areas will likely see expanded interest. The first is in further development and improvement of bonding, either by improved adhesives or investigation into the benefits of methods like diffusion to address the primary issue in patch repairs, debonding. Research into the use of additive manufacturing technology for repair, especially of non-fusion-based methods, is likely to increase as the use of these AM technologies in manufacturing expands. Further investigation into the combination of various repair techniques and their potential synergistic effects is expected, as the need for repairs that provide a more significant increase in product lifetime becomes more desirable with the increasing cost of many systems, especially in aerospace.

Chapter 7

Summary

This literature review on aluminum fatigue was done to develop knowledge on the state of research into the subject area across the engineering disciplines, from design to production to in-service maintenance and repair. As the goal was mainly to gain knowledge on the field, a sensible place to start was the beginning of the field.

A brief history of research into the topic was developed to gain background into current research efforts, focusing on three key periods. The first was defined as lasting from the start of the field in the 1830s to the shift in interest from railways to aircraft-centric work in the 1910s. In this first period, a phenomenological understanding of fatigue is established through observing failure and developing experimental procedures to test the fatigue lifetime under specific conditions. In the following period spanning from the 1910s to the 1960s, better models of the stress, strain, and damage during fatigue cycles were developed with other important work in manufacturing processes that improved the fatigue life of materials and the systematic investigation of their fatigue performance. The final period started in the 1960s, when crack growth became more important, leading to an increasingly multi-disciplinary field involving materials science, mechanical properties, and fracture work. In this, it is evident that the research is always heavily motivated by issues in industry, very often by transport-related accidents, including early train-axle fatigue failures to later aircraft wing and fuselage failures driving news cycles and money into the field of fatigue research. This research has also generated positive results, with the rate of fatigue-related incidents dropping drastically over time. However, it is still the most common source of failure in mechanical systems and, as such, warrants continued research.

The method of aluminum production is the most significant single influencing factor on fatigue life outside of part design. In evaluating the fatigue performance of various manufacturing methods, the presence and distribution of defects in the material that are created during production is of great importance. Research into the development of statistical models to describe the presence of defects in the material is widespread. These models are being used to evaluate materials of various production methods to establish statistical standards on the presence of defects to help integrate such information better into multi-scale fatigue modeling. During manufacturing, a common source of fatigue crack initiation is the location and method used in joining parts together. Specific investigations into the effects of riveting and welding were researched to evaluate their relative pros and cons without directly comparing these methods.

The inspection of materials and parts has been a cornerstone of fatigue failure mitigation since the start of the field. In recent years this research has focused more on the automation and computerization of existing methods over developing novel techniques. These combined effects have resulted in Eddy Current, Ultrasonic, X-ray, and thermographic inspections that can be done more quickly, detect more minor flaws than previously, and in some cases be done without operators such as autonomous X-ray inspections that automatically traverse along the fuselage of an aircraft in a preset inspection pattern. Additionally, the decreased costs of installed sensors such as strain/load sensors, ultrasonic piezoelectrics, or optics in the aircraft structure and lower cost data storage have allowed operational data to be recorded at multiple points in a system over its entire operational life. These systems, commonly known as structural health monitoring systems, can diagnose likely damage and provide data to complex machine learning models that develop improved fatigue lifetime, damage prediction, and detection algorithms that allow for reduced inspections and increased accuracy of fatigue models and safety standards.

The ability to repair damage caused by fatigue is widespread and highly effective at extending the service life of fatigued systems. Research into improving existing methods, including crack-stop holes, bonded patch application, surface renewal, and crack welding, accounts for a large amount of literature in the field. These methods are still being investigated to compare their effectiveness in extending the fatigue life and retarding crack growth, and integrating new technologies such as smart patches with integrated sensors. The development of new methods, especially the extension of additive manufacturing into crack filling and fusion repairs, is a promising new process that is being thoroughly researched due to additive manufacturing's recent popularity. A valuable area of further exploration is the combination of different repair methods to improve the performance of the repaired structure. This is likely to remain a popular field of research as the cost-effectiveness of repairs compared to new systems is very likely to endure.

Research into aluminum fatigue is growing, with an increasing number of papers published each year. In all aspects of study, miniaturization and improvements in computer technology have resulted in leaps forward in understanding production, monitoring, and data analysis. These developments are addressing a long-standing issue with fatigue modeling where inaccurate or incomplete data on load histories has hampered the accuracy of different models. Additionally, increased computing power is likely to continue recent improvements in modeling. Indeed, the ability to simulate the more complex aspects of fatigue will likely result in improved models that reduce the number of fatigue failures. However, fatigue will likely continue to be a consideration in design that needs to be balanced alongside others, such as weight, size, and cost, but with increasingly useful data to make the decision.

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