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CRACK GROWTH INVESTIGATION OF ALUMINUM FIBER METAL
LAMINATES UNDER FATIGUE LOADING

By
Sarah Elizabeth Gutierrez
B.S. University of Louisville, 2004

A Thesis
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in Partial Fulfillment of the Requirements
for the Professional Degree

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Department of Mechanical Engineering
University of Louisville
Louisville, Kentucky

August 2005

CRACK GROWTH INVESTIGATION OF ALUMINUM FIBER METAL
LAMINATES UNDER FATIGUE LOADING

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A Thesis Approved on

7-28-05
(Date)

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Dr. James C. Watters, Department of Chemical Engineering

DEDICATION

This thesis is dedicated to my loving parents

Mr. Dan Gutierrez

And

Mrs. Debora Gutierrez

for their unconditional love and support and their dedication to my education through so many years.

ACKNOWLEDGEMENTS

First and foremost, I want to thank my personal savior Jesus Christ. Without Him I could do nothing. I would like to thank my loving parents. Their hard work and endurance got me to where I am today. They invested more time in home schooling me than I can ever thank them for. My mom has taught me what it is to be a wonderful mother and my dad has always been my role model. If it were not for him and his ability to succeed at everything, I would not have chosen engineering. Also I want to thank my wonderful fiancé for his love, encouragement and support.

Greatest appreciation goes out to Dr. Roger Bradshaw for his guidance and wisdom throughout this thesis. I would like to thank Dr. Hnat for sharing his knowledge and aid on the MTS machine. I would like to thank The Boeing Company for my support under the grant “Fatigue and Crack Growth Investigation for Aluminum Fiber Metal Laminates” and Bill Westre, Ed Li and Matt Miller at Boeing for their help and support on this project. Thank you to Dr. Watters for serving on my committee. A special thanks to John Jones for all of his hard work in the Mechanical Engineering shop and John Osborne for his previous work on TiGr fatigue.

ABSTRACT

Aluminum fiber metal laminates (AFMLs) are a promising new type of fiber metal laminate that consists of aluminum foils interleaved with layers of a graphite fiber-polymer matrix composite (PMC) material. AFMLs combine the attractive features of aluminum with the advantages of traditional graphite polymer-matrix composite. There are a number of anticipated benefits of such a material including weight reduction, improved bearing capability and high conductivity for lightning strike protection. The presence of the fiber-reinforced composite also provides a method to arrest cracks in the aluminum layers via fiber bridging.

In order to understand crack initiation and growth in AFML specimens, this study considers the tensions-tension fatigue response of 39 AFML specimens at five different stress levels and three different specimen configurations. The specimens and support for the project was provided by The Boeing Company (Structures Damage and Technology Group). Several methods of crack investigation were considered for this study; it was determined that visual inspection through digital photography at evenly spaced intervals throughout the test provided the best method for the characterization of crack initiation and growth.

Visual analysis of the specimen images was performed. This led to precise estimates of the cycles to crack initiation as well as crack length versus cycle count throughout each experiment. The results clearly demonstrated reduced crack growth rates throughout each experiment, which is likely attributed to fiber bridging. Crack growth versus cycles for various experiments were well represented by a single reference curve with appropriate cycle count scale factors. This demonstrates that linear elastic fracture mechanics appears to govern the crack growth response. This project demonstrates the

value of visual imaging to monitor crack initiation and growth in AFMLs and offers a potential method to better understanding the phenomenon in future studies.

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I. INTRODUCTION

A. Background Information

Commercial transport aircraft are beginning to use composite materials in their primary structure. Primary structure includes the critical structural components of the wings, fuselage, and empennage. Boeing has announced that the majority of the primary structure, including the fuselage and wing, of the new 787 (“Dreamliner”) aircraft will be made of composite materials (Boeing 787, 2005). Presently, traditional graphite fiber reinforced polymer-matrix composite (PMC) is used in several aerospace applications; these include the Boeing 777 vertical fin, horizontal stabilizer and cabin floor beams, with composites totaling nine percent of the entire structure (Boeing 777, 2005; Dustman, 2004). The new Airbus A380, which recently completed its first flight, benefits from weight savings of traditional composites as well as GLARE (glass-reinforced fiber metal laminate) which comprise 25% of its structure (Airbus, 2005). Traditional PMC systems have a beneficial weight savings but several negatives including more complicated design, increased fabrication costs relative to aluminum, sensitivity to impact damage and low bearing strength (AIAA, 2004).

Fiber metal laminates (FMLs) have been researched and developed since the 1970s. Metal foils or sheets are combined with traditional PMC to create FMLs. Like traditional PMC materials, FMLs offer weight savings relative to current metallic structures and require fewer components to construct parts than when using metal alloys. The benefits of the metallic layers are also attained along with superior fatigue properties, damage tolerant behavior, inherent resistance to corrosion, improved bearing strength and good fire resistance. These properties make FMLs very attractive candidates for future aircraft structures (Asundi and Choi, 1997; Li, 1998).

One attractive feature of FMLs is the fiber bridging characteristic of the PMC fibers. Compared to traditional aerospace grade aluminum open hole tension fatigue tests, FMLs display excellent crack retardation (Takamatsu, et al., 1999; Burianek, 2001; Gunnink and Vlot, 2001; Bradshaw and Gutierrez, 2005). Cracks in aluminum sheets will generally grow at an ever-increasing crack growth rate; as such, special crack-arrest features are often used to prevent catastrophic failure before crack detection and repair occurs. In FMLs, however, the cracks in the metallic layers are surrounded by PMC layers containing continuous fibers. As the crack attempts to open and advance, the fibers prevent this by “bridging” the crack. This effectively reduces the stresses that exist at the crack tip, resulting in a lower rate of crack growth compared to the metal layer alone (Li, 1998; Li and Johnson, 1998). The problem of crack initiation and growth, or the fiber bridging properties, through fatigue tests is complex and dependent on many different factors. Understanding the crack growth characteristics of FMLs remains one of the challenges for these breakthrough materials. The effect that PMC layup, PMC/metal ply thicknesses, orientation of PMC plies against the metallic layers have are only a few of the research questions of interest.

Several FMLs have been researched and studied for crack growth properties in fatigue. ARALL (Aramid Reinforced Aluminum Laminate) was introduced by the faculty of Aerospace Engineering at the Delft University of Technology (DUT) in 1978 (Asundi and Choi, 1997). ARALL was found to suffer from corrosion between the aluminum and PMC system as well as having several other structural difficulties. GLARE was also introduced at DUT around 1990. GLARE has achieved more widespread use and has been studied extensively (Takamatsu, et al., 1999; Asundi and Choi, 1997; Gunnink and Vlot, 2001; Baten, Boer and Wittneberg, 2001). Over the past

10-15 years, another FML material called TiGr has been considered; TiGr consists of a combination of thin titanium foils and graphite fiber reinforced PMC. Graphite fibers are superior in stiffness, strength and weight to the glass fibers used in GLARE and the incorporation of titanium leads to a fatigue-resistant material that has high strength / stiffness properties and is well-suited for high-temperature applications (Bradshaw, 2002; Bradshaw and Osborne, 2004; Burianek and Spearing, 2002; Burianek, Giannakopoulos, and Spearing, 2003; Li, 1998; Li and Johnson, 1998).

A variety of methods to understand crack initiation and growth in FMLs have been used. One approach is visual inspection, monitoring the specimen visually and noting when a certain crack length is obtained (Osborne, 2004). However, this method is not practical unless the metallic layer is on the surface of the specimen. Another approach is electrical measurements, using changes in the resistance of the metallic layers as an indicator of crack length; for example, GLARE specimens with interior aluminum layers were tested under constant amplitude loading with crack length monitored via the DC electrical potential-drop method (Takamatsu, et al., 1999). Another approach uses extensometers to detect changes in specimen stiffness, deducing crack growth from the appropriate modeling methods. Other methods such as x-ray inspection (Bradshaw, 2002; Burianek, 2001) and destructive visual inspection (Burianek and Spearing, 2002) can also be used.

B. Purpose of Thesis

The purpose of this thesis is to study the crack initiation and growth behavior of open hole aluminum fiber metal laminates under tension-tension fatigue. Characterization of the crack behavior was considered using visual inspection via digital photography and stiffness loss measurements using extensometers. Analysis of the visual record provides

a detailed data set for each specimen in terms of cycles to crack initiation and crack length throughout the experiment. This thesis analyzes the data resulting from the various tests, demonstrating a number of useful findings relative to the fatigue behavior of the AFML specimens. The specimens and support for this project were provided by The Boeing Company (Structures Damage and Technology Group) as part of the grant entitled "Fatigue and Crack Growth Investigation for Aluminum Fiber Metal Laminates" (principal investigator: Dr. Roger D. Bradshaw).

II. AFML Specimens

In this section, details of the AFML specimens will be presented. This includes the layup of the specimens, the various specimen preparations considered during the study and methods of painting the specimens to achieve optimal contrast for digital photography.

A. Specimen Layup

The aluminum fiber metal laminates considered in this study are constructed with thin (0.203 mm/0.008 in) foils of an aerospace-grade aluminum (2024-T3 series) and graphite-fiber reinforced PMC plies (0.188 mm/0.0074 in per ply) suitable for aerospace structure. The Boeing Company fabricated a single panel consisting of two outer aluminum plies (top and bottom) and 14 interior PMC plies. A typical panel schematic with ply directions is shown in Figure 1. The panel in this study consisted of a combination of 0, ± 45 and 90 degree plies. The panel layup is symmetric and can be written as $[A1 / +45 / \dots]_s$, where the unstated plies lead to a balanced panel (equal number of +45 and -45 plies) with behavior similar to aircraft wing skins subjected to largely uniaxial loads in the 0 direction.¹ This panel was cured at 350°F; all fabrication and testing was performed at room temperature.

¹ Certain information pertaining to the fabrication and layup of the AFML panel is proprietary information of The Boeing Company and will not be presented.

Figure 1. Ply angles and load direction of a typical specimen.

(Angles as viewed from top or “bag side” of panel)

The panel was then cut into 39 specimens with typical test coupon dimensions of 38.1 mm (1.5 in) wide x 305 mm (12 in) long (in 0 direction) with a centrally located 6.35 mm (0.25 in) diameter (nominal) hole. The hole is left open (i.e. no fasteners inserted), which provides a crack initiation site during the fatigue test and is also representative of stress concentrations in aircraft structure (assuming a loose fastener). The holes in this study were first drilled 6.35/6.45 mm (0.250/0.254 in)². A majority of the holes were then reamed 6.53/6.58 mm diameter (0.257/0.259 in), a standard approach to improving hole quality after drilling (these specimen will be referred to as baseline or reamed specimen). The remaining specimens used a hole finishing method called jig grinding, in which a high-speed oscillating grinding tool is used to polish the hole

² The two diameter values, i.e. 6.35/6.45, are hole tolerance values. Acceptable hole diameters are in the range of 6.35 mm- 6.45 mm. The same is true when considering reamed hole diameters.

interior; the same finished 6.53/6.58 mm (0.257/0.259 in) diameter was obtained as in the reamed specimens. A subset of the reamed, or baseline, specimens were subjected to shot peening after the holes were drilled but before reaming. At the aluminum surface shot peening is a basic plastic deformation process using the impact of small balls to produce beneficial compressive stresses within the material. Small balls are thrown at high velocities against the metal sheets creating dimples in the material resulting in compressive stresses (Fuchs and Stephens, 1980; Everett, et al., 2001). Small glass balls were used to shot peen by the Boeing Company (the intensity and details of this process are proprietary and will not be discussed) and the dimples resulting from this process are not visible to the naked eye (Westre, 2004). The curing process of the FML causes residual stresses in the PMC due to the thermal strains, resin cure shrinkage, gradients in temperature and resin degree of cure, and tooling mechanical constraints (Baker, Dutton and Kelly, 2004). It can be argued that the residual stresses, tension stresses due to the orientation of the 0 degree plies, are relieved through the compressive stresses induced by shot peening. Studies show that shot peening aluminum increases the time to failure between a factor of 2 and 4 for low stress levels and 1.2 to 2.7 for higher stresses (Everett, et al., 2001). Phenolic blocks were attached to both ends of the specimen to prevent slipping and crushing of the specimen when gripped for testing. A schematic of a typical specimen is shown in Figure 2. All specimen fabrication was performed by The Boeing Company except that phenolic blocks were cut and attached to both sides by the author at the University of Louisville. Most specimens were studied under tension-tension fatigue; a limited number were subjected to a static test to failure to establish the open hole tension (OHT) strength of the specimen.

Figure 2. Top and side view of typical AFML specimen.

The reamed specimens with no surface modification (i.e. not shot peened) are referred to as the baseline specimens. Two variants on the baseline specimens exist: 1) jig ground holes with no surface modifications; and 2) shot peened surface with reamed holes. These variant specimens provide a method to understand the effect of the alternate hole finishing method (jig grinding) and surface modification (shot peening).

B. Painted Surface Preparation

Visual inspection via digital photography is one of the methods used for crack detection in this project. However, fatigue cracks that occur during testing are difficult to detect for the as-received AFML specimens due to the lack of contrast between the aluminum surface and cracks. To improve contrast for crack detection, the aluminum surfaces of each specimen were coated with a thin layer of white enamel spray paint, applied to a 2" high region centered about the open hole (applied by The Boeing Company). However, the type of paint used and method of application lead to a textured paint surface instead of the glossy surface that had worked well in the previous fatigue study of TiGr laminates (Osborne, 2004). Crack detection was much more challenging

for a textured paint surface; as such, a method to reduce the texture was developed. This was achieved by lightly wet sanding the specimens using a 400 grit emory paper. The emory paper was not allowed to scratch the underlying aluminum layer (although some spalling of the paint, especially around the hole, did occur). Figure 3 shows the region in the vicinity of the hole for an as-received specimen and another specimen after wet sanding. The paint texture is much less noticeable after sanding, improving contrast for crack detection.

Figure 3. Digital photographs of two specimens: (top) as-received paint texture; (bottom) paint texture after wet sanding.

III. Test Equipment and Procedure

In this section, details of the test equipment and procedure will be presented. This includes the MTS servo-hydraulic test frame, extensometers, digital cameras and data acquisition / experiment control system. The approach is similar to that used in a previous fatigue study of TiGr laminates at the University of Louisville (Osborne, 2004). Several changes were made for this study including the use of dual digital cameras and the ability to specify test parameters such as cycles per picture. The test equipment and procedure were validated prior to testing the AFML specimens via extensive testing on both aluminum and aluminum-polyethylene sandwich specimens with open holes.

A. Material Testing System

The fatigue tests were conducting using the MTS 810 servo-hydraulic material testing system shown in Figure 4. The MTS 810 is designed to accommodate a wide variety of standard materials tests (MTS Guide, 1990). The MTS 810 has the upper limits of ± 89 kN (± 20 kips) load and ± 127 mm (± 5 inch) displacement. The system controller (shown in Figure 5) consists of a MicroConsole 458.20, primarily used for materials testing, an AC controller for displacement control, DC controllers for load control and two extensometers, and a MicroProfiler. The series 632 Axial Extensometers (shown in Figure 6) are used for a variety of tests including tension/compression testing, low and high cycle fatigue, creep/stress relaxation testing and strain rate testing.

Figure 4. Picture of MTS System.

Figure 5. MTS System Control Box

Figure 6. MTS Extensometer

Testing can be performed while operating under load control or displacement control. A test can be specified through a program integrated in the MicroProfiler or a remote program from an external computer. Displacement control via the MiroProfiler was used for the static tension test to failure (establishes the open hole tension (OHT) strength). In load control, the user specifies the load to be applied. The fatigue tests were

performed under load control, with load options specified by a PC attached to the system controller.

Measuring displacement centrally about the open hole during fatigue testing is one way of detecting stiffness loss due to crack growth. To accomplish this, the extensometers were mounted on each edge of the specimen using springs during testing, as shown in Figure 7; the extensometer points were centered about the hole. It would be preferred to mount these on the front/back of the specimen on the centerline (i.e. spanning the hole). However this obstructs the view of the digital cameras and as such could not be used. As utilized, the extensometers have a range of ± 5.08 mm (± 0.2 inches).

Figure 7. Extensometers mounted on either side of specimen using springs.

B. Digital Cameras

Crack initiation and growth in the AFML specimens was monitored using digital imaging. Two Nikon Coolpix 5700 digital cameras (5.0 mega pixels, maximum image size) with two slave flashes each were mounted on either side of the AFML specimens as shown in Figure 8. The cameras were attached to plastic mounting platforms built at the University of Louisville which were attached to the MTS machine (shown in Figure 9).

These platforms allowed the cameras to be positioned by moving the camera towards or away from the specimen (left/right) and while also allowing the camera to be centered on the open hole (up/down). Each camera was connected to the data acquisition computer through serial cables connected to the serial ports of the computer. A LabVIEW program triggered each camera to take a picture by sending a series of hexadecimal commands to the serial ports (Osborne, 2004).

Figure 8. MTS Machine with specimen loaded and camera set up.

Figure 9. Camera platform mounted on MTS frame.

By operating the cameras in manual mode, important features such as macro mode, exposure mode, shutter speed, film speed³ and flash settings could be specified. Macro mode enables the user to focus on an object within 30.48 mm (1.2 in) from the lens. The cameras' internal "pop-up" flash units were completely covered using layers of white paper to prevent glare. Instead, two external flash units per camera (see Figure 8) were used to produce the proper lighting. The external flashes are ProMaster FT 1700 controlled through the hot shoe of the Nikon cameras; each flash was modified at the University of Louisville to run on power supplied by an AC adapter and clamped to the platforms using special c-clamps designed for external flash units.

Because these external flash units are "dummy" flashes that cannot control their own light output, special features are selected within each Nikon camera. The shutter speed regulates how long the film is exposed to light coming through the lens. For

³ Films speed refers to the films sensitivity to light. In digital photography film speed refers to an equivalent setting to 35mm photography although no actual film is used.

overexposed pictures the shutter speed is set to 1/4000s. A variable power of -2.0EV prevents the flashes from burning out too easily. The F-stop regulates how much light is allowed through the lens by varying the area of the hole the light comes through. For the optimal combination of film speed and lighting conditions, an F-stop of 6 or higher was used. A 100 ISO, film speed, was used which is adequate for most well lit objects. Each external flash unit had two settings based upon the distance of the object being photographed, near and far; the near setting was selected. Finally, to prevent specimen glare and diffuse the light, each external flash was diffused by covering the flash portion with paper of appropriate density. A side front view of the camera/flash set up is shown in Figure 10.

Figure 10. Side-front view of camera set up.

C. Test Load Steps

The tension-tension fatigue tests consist of three load steps that are repeated until the total cycle count is achieved. The first step is an N-1 fast cycle count ranging between 10% and 100% of the maximum load ($R = 0.1$) cycled at 7.5 Hz. The value of N is specified based upon the total amount of cycles desired per captured picture. The second step is a slow cycle (0.1 Hz) between the same load limits. This slow cycle provides a detailed load-displacement history for the specimen that could be used to determine stiffness loss assessment. The last step loads the specimen to 50% of the maximum load and holds for a specified time (typically 24 seconds), during which pictures are taken of the specimen surfaces. The applied load is intended to make the cracks more visible while remaining small enough to avoid further crack propagation. A schematic of a single set of the three load steps is shown in Figure 11.

Figure 11. Schematic of the three load steps leading to N fatigue cycles and 1 picture set.

This set of load steps completes N fatigue cycles; the steps are repeated M times until the desired total cycles count ($M \times N$) is completed. A BASIC program to remotely control the loading was written by John Osborne; this runs on the computer attached to the MTS MicroProfiler. The program sends ASCII commands to the MicroProfiler in order to complete M repeats of the 3 load steps shown above. (Osborne, 2004)

D. Data Acquisition using LabVIEW

National Instruments LabVIEW, a powerful graphical programming data acquisition software package, was used to capture the test data through a computer containing a 12 bit data acquisition card (Osborne, 2004). The program (also called a Virtual Instrument or VI) was written by Dr. Roger Bradshaw and was modified for the current study. The VI is set up to capture the load, MTS head displacement and displacement readings from extensometers 1 and 2. The VI automatically determines which of the 3 load portions it is in at a given moment (see Figure 11); it does this by sensing the 0 load points that occur between each step. During the fast cycle portion, the VI determines the data associated with the maximum and minimum recorded load values during each cycle and writes them to a text file. During the slow load cycle, 20 data points per second are collected and written to another text file. During the third load step, the VI triggers each camera in succession to take a picture; this is done by sending serial commands in the same command language used by the remote control unit for the Nikon Coolpix 5700 cameras (these commands can be found in Osborne, 2004).

The front panel of the LabVIEW program is shown in Figure 12. The user specifies the maximum load, the R value for the test, test file name, load cell module (20 kips was typically used in this study) and whether cameras are to be used or not. As previously mentioned, the cameras are controlled via a cable attached to the serial ports

of the LabVIEW PC; the ports to be used are also specified in the VI. Once a test is running, the current cycle count and various load data is shown on the screen to inform the user of the ongoing test status. The data from the fast and slow cycles load steps is saved to the files named “File_Name_max.ftd” and “File_Name_slow.ftd”, respectively, where File_Name is the value entered by the user. The “..._max.ftd” file is generally quite large as it contains $M \times N-1$ text lines (i.e. one line for each fast cycle).

Figure 12. LabVIEW front panel of data acquisition program.

E. Fatigue Test Procedure

Each fatigue test specimen required a process of set up and execution. First, each specimen was wet sanded to reduce paint texture as described in Chapter II. A self-adhesive label was then placed on both sides for documentation; this label also provided a clear item which was used to focus the cameras. The as-received specimens were labeled with the panel name and specimen number (-01 to -39) by The Boeing Company with a paint marker on only one side. Through microscopic inspection it was verified that this is the “bag side” of the panel (the top of the panel layup) as opposed to the “tool side” (or

bottom) of the panel. The “Right Side” label was always placed on the side with the hand-written Boeing labels with the “Left Side” label then placed on the other (unmarked) side. This distinction will be important when the effect of fiber orientation against the aluminum is considered. A small ink pen mark was placed at the locations for the two extensometers to be mounted on the specimen; the marks were centered around the hole.

The first step in mounting a specimen in the MTS is to first issue a “return to 0” command on the MicroProfiler, which returns the bottom head of the MTS to its original position. This was always done before inserting a specimen into the MTS in order to avoid unintended crushing or fracture of the specimen. The specimen was then inserted into the hydraulic grips of the MTS machine using displacement control to move the grips into the desired position. The hydraulic grips were then activated; a grip pressure of 7-10 MPa (1000-1500 psi) was typically used. Once the grips were both locked the control was quickly switched to load control.⁴ The starting load was adjusted to 0 lbs.

A small amount of M-Bond 200 strain gage adhesive was applied to the marked locations on the specimen where the extensometer points were to be located; this glues the extensometer points to the specimen in order to eliminate slippage during the fatigue tests. Both extensometers were mounted using four small springs as seen in Figure 10; pins were placed in the extensometers to hold them at a reference spacing of 25.40 mm (1.000”) during mounting. The extensometers were allowed to set for approximately 20 minutes to allow the adhesive to cure. The DC controllers for extensometer 1 and 2 were then balanced; afterwards the pins were removed.

⁴ In order to make the transition smoothly from displacement control to load control the DC error output displayed on the MicroConsole was monitored while turning the load dial in the direction indicated by the illuminated arrow. Once the DC error got close to zero, the switch from displacement to load control would take place. By changing control methods in this manner, an overload (and possible failure) of the specimen could be avoided.

Both cameras were then prepared for the experiment. First, all previous pictures were downloaded from the 1 megabyte flash cards and erased. The picture numbering was reset for each test using the camera settings so that each set of pictures was numbered from 1-500 (for 500 pictures per side). The highest resolution (5 mega pixels, 2560 x 1920 image size) was used with minimal image compression⁵. The cameras were then attached to the mounts shown in Figure 9. The camera position was adjusted until the specimen hole was centered and the specimen width nearly filled the camera field of view. The focus of the specimen was attained automatically by the camera using the specimen label as the focus area. All settings were then locked, which prevents the camera from changing its settings during the test. A trial picture was then taken and checked to ensure the quality of the pictures; this trial picture is deleted prior to the start of the test.

Due to the high specimen stiffness and short cycle duration, the MTS maximum and minimum attained loads during the fast (7.5 Hz) cycles are often less than those specified by the user. To account for this, the MTS is commanded to attain loads that lead to actual maximum and minimum loads that match the desired values. Several trial runs, consisting of 20-30 fast cycles each, were performed to identify the commanded loads for each specimen. These values were then used as the input for the BASIC program that controls the MTS during the fatigue test.

To start an actual fatigue test, the “Run” button is depressed on the LabVIEW VI after all inputs are completed. The VI then waits for the first specimen loading to trigger it to begin collecting test data. The “Run” button is then depressed on the MicroConsole. Then the inputs to the BASIC program on the computer next to the MTS are completed;

⁵ Raw images without compression could be taken but this would drastically limit the storage space on the memory cards; as specified above 800 pictures could be stored on each flash card.

this begins the process of sending commands to the MTS that will control the experiment until it is finished.

This process was completed for each fatigue tests. Once a test is finished, the data files (“..._max.ftd”, “..._slow.ftd”) are closed by LabVIEW and are ready for analysis. The MTS “return to 0” button is depressed and the specimen is removed using load control. The pictures contained on the flash cards of each camera are downloaded to a computer for analysis.

F. Open Hole Tension (OHT) Test Procedure and Parameters

Another type of test was also conducted using the MTS during this study. This is a static tension test to failure used to determine the open hole tension (OHT) strength of the specimens. The specimen was mounted in the MTS using extensometers similar to the approach described above. The specimen was then tested in displacement control, via a program contained in the MTS controller, at the rate of 1.27 mm/min (0.05 in/min) until failure occurred; this is a standard rate used by Boeing in static tests. Data collection was performed using a LabVIEW VI. Three baseline specimens and one shot peened specimen were so tested. The open hole tension strength for each specimen (σ_{OHT}) was then calculated using

$$\sigma_{OHT} = \frac{P_{max}}{W t} \quad (1)$$

where P_{max} is the maximum load at failure and W and t are the width and thickness of the specimen, respectively. This calculation is based upon the cross-sectional area far from the hole (i.e. the hole area is not subtracted when calculating σ_{OHT}). The three baseline OHT test results were averaged to obtain a baseline OHT stress; these values were very similar, with a coefficient of variation (CV = standard deviation / average) of 1.13%.

Each of the three OHT stresses are presented in Table 1 as scale factors ∇^6 , calculated via the formula

$$\nabla = \frac{\sigma_n}{\sigma_{avg}} \quad (2)$$

where σ_n is the OHT stress of the specimen and σ_{avg} is the average of the three baseline OHT stresses. As mentioned above, one shot peened specimen was also tested to determine its OHT stress. This was done to assess whether the shot peening process significantly changed the OHT strength of the specimen. The scale factor for this test is also provided in Table 1; the baseline OHT stress is used to calculate this value. Although this result is only for 1 specimen, it is reasonable to conclude based on the small CV of the baseline specimens that this result is representative of shot peened specimens. As such, it is apparent that shot peening does not change the OHT strength in an appreciable way.

Specimen	Specimen Type	OHTn/OHTavg
-1	Reamed	1.012
-2	Reamed	0.998
-3	Reamed	0.990
-32	Shot Peened	1.014

Table 1. OHT stress level scale factors.

G. Fatigue Stress Levels

The fatigue testing in this study was to be performed at various stress levels sufficient to lead to significant crack growth during the period of study for each specimen. To establish the stress levels and cycle counts to be used, two calibration tests

⁶ The presentation of OHT stresses as scale factors of the average stress is done because the OHT stresses obtained during testing are proprietary. Similarly, stress levels used during fatigue testing will not be specified directly; rather, they will be reported as a percentage of the average OHT stress.

were performed with a maximum stress of 0.40 OHT and 0.55 OHT. The cycle count was recorded for each specimen at the moment of crack initiation, when the crack length reached one hole radius in length, and when the crack tip reached 90% of the specimen width; the resulting values are listed in Table 2. Based on these findings, the maximum stress levels were set to 25.0%, 32.5%, 40.0%, 47.5% and 55.0% OHT with corresponding cycle counts shown in Table 3. It was anticipated that these stress levels and cycle counts would lead to the crack lengths that would nearly span the width of the specimen by the conclusion of each test. In every case, 500 repeats of the load step cycle were completed, leading to 500 images collected for each side of the specimen during each test (see Figure 11).

OHT Stress	#Cycles(K) for:		
	Crack Initiation	1R Length	90% Specimen Width
0.55	20	82	450
0.40	45	137	1000

Table 2. Results from initial calibration tests on two specimens.

Maximum Stress / OHT Stress	Total Fatigue Cycles (M*N)	Cycles Per Picture (N)	Number of Step Repeats (M)
0.550	500,000	1,000	500
0.475	750,000	1,500	500
0.400	1,000,000	2,000	500
0.325	1,500,000	3,000	500
0.250	2,000,000	4,000	500

Table 3. Fatigue details for maximum stress, total cycles and cycles per picture.

IV. Analysis

A. Digital Image Analysis

After the fatigue tests were completed, characterization of crack growth was based upon the analysis of the collected data. For the metallic layers in the AFML, the most valuable means of analysis is visual inspection. Two sets of images were obtained from the cameras. The “Left Side” and “Right Side” results were associated with the cameras on the left and right side, respectively, when facing the MTS as in Figure 8. As previously stated, the “Right Side” corresponds to the “bag side” of the AFML panel while the “Left Side” corresponds to the “tool side.” The left side pictures were then renamed using BulkRename Utility⁷ as odd numbered pictures (0001, 0003, ...) while the right side pictures were renamed as even numbered pictures (0000, 0002, ...). These images were stored in a single folder on the analysis PC.

Representative images from the left and right sides were opened using Microsoft Photo Editor. An appropriate image crop size was selected (in terms of the location of the cropped upper left corner as well as cropped height and width, all in pixels). The image crop allows unnecessary features in each image, such as the extensometer springs, to be eliminated. The pictures were then processed using a program called ImageJ.⁸ This was done using a macro called “Build_Montage,” written by Dr. Roger Bradshaw and provided in the Appendix. First, ImageJ opens each pair of images (left and right sides) at a given cycle count. The macro then takes the right and left side and crops them to the desired size as described above and joins them together creating a montage for each cycle

⁷ BulkRename Utility is freeware created by Jim Willsher that allow large quantities of files to be renamed simultaneously. It can be obtained at <http://www.bulkrenameutility.co.uk>.

⁸ ImageJ is a public domain software package developed by W.S. Rasband at the U.S. National Institutes of Health, Bethesda, MD, USA. It can be downloaded at <http://rsb.info.nih.gov/ij/>.

count (right side image on top, left side image on bottom). Each picture montage, similar to Figure 13, is sequentially ordered from first cycle to last cycle for ease of viewing.

Figure 13. Montage of the left and right side of specimen 26.
(cracks have been manually highlighted)

A typical crack growth history would appear as in Figure 14. The crack is first visible at 72 K cycles; this is referred to as crack initiation. The second crack initiates at 378 K cycles. The first crack grows to more than half of its final length by 786 K cycles, with the crack growing at a slower rate until the final image at 1,500 K cycles. This type of growth (slower rate as length increases) is due to the crack fiber bridging provided by the PMC layers adjacent to the aluminum plies. The cracks in Figure 13 and Figure 14 have been manually highlighted with a thin black line in Microsoft Paint, a process that is very time consuming. The procedure of highlighting the cracks was simplified by

ImageJ, which contains many powerful tools that make it ideal for image analysis. The most valuable feature for this study was “Find Edge,” which automatically obtains an excellent representation of the crack without manually touching up the pictures. This is done using an edge detection method that identifies and locates sharp discontinuities in an image through a high pass filter. Figure 13 showed a typical set of images with cracks manually highlighted. Figure 15 shows the result for the same image obtained by ImageJ using the “Find Edge” feature; the original montage image was used for this analysis (i.e. the analysis was not performed on an image with manually highlighted cracks as in Figure 13). This procedure was successful for identifying cracks for most images; the exception was certain shot peened specimens for which cracks were very difficult to detect using anything other than the original color images. The “Build_Montage” macro automatically performs this analysis for all images obtained during the experiment, resulting in 500 montage images with cracks identified using the “Find Edge” feature. Montages were then imported into BulkRename Utility after they had been processed and appropriately named to reflect their respective cycle count.

Figure 14. Specimen 26 fatigued at 32.5% OHT at the crack cycles indicated.
(lefts side; these cracks have been manually highlighted)

Figure 15. Montage of the left and right side of specimen 26 with “Find Edge” feature.
(cracks are as obtained by ImageJ and have not manually highlighted)

B. Crack Growth Analysis

Several important aspects of the cracks that occur during the fatigue test are obtained for each specimen. These include crack length, path, and rate of growth as a function of fatigue cycle count and associated stress levels. The processed digital images are initially reviewed and a subset of images (generally 15-30) are selected to characterize the behavior of each crack on the specimen. These images begin with the first crack initiation on the specimen and end with the final image of the experiment. Each montage is opened in ImageJ and the position of all crack tips are measured as x and y pixel locations. Cracks are named numerically based on their location on the specimen with cracks on each side beginning at 1. The order of numbering is from top to

bottom for the cracks to the left of the hole and then from top to bottom for the cracks on the right side of the hole. Each crack is also given a letter designation, beginning at A and continuing B, C, ...; the order corresponds to the order in which the cracks initiated on the specimen, with A occurring before B and so on. For cracks that initiated simultaneously, the same letter is assigned to all. An example is shown in Figure 16. In order to verify the accuracy of the crack data versus cycle count, all collected crack tip points were then overlaid in Excel on an appropriately scaled montage from the last cycle. The points were visually verified to start at the hole and lie along the crack path; this provided an opportunity to catch errors in the data. For completeness, the pixel locations of the quadrants of the circle are also noted and shown on the associated plot. Figure 17 shows the crack tip points plotted against the actual image. Each point represents the crack tip data collected at a certain cycle.

Figure 16. Specimen 10 montage with crack labels (0.475 OHT x 750K cycles).

Figure 17. Crack pattern of specimen 10 plotted with montage image as background. (each point represents a crack tip location data point collected at a certain cycle or a quadrant part of the hole).

These pixel locations are imported into an Excel spreadsheet. The crack length is calculated using

$$L_i = L_{i-1} + \alpha * \sqrt{(w_i - w_{i-1})^2 + (h_i - h_{i-1})^2} \quad (3)$$

where α is a conversion factor relating the length (in mm) per pixel for each image, L is the crack length and w and h are the horizontal and vertical pixel locations of the crack tip, respectively, and the subscripts i and $i-1$ refer to the current and previous data points, respectively. The conversion factor α is found by the equation

$$\alpha = \frac{38.1}{\Delta} \quad (4)$$

where the value 38.1 is the width of the actual specimen (in mm) and Δ is the width of the specimen in pixels (measured in ImageJ).

For each crack on a specimen the overall crack angle was calculated to determine the importance of ply orientation. Each crack angle was calculated using

$$\Theta = \tan^{-1}\left(\frac{\Delta y}{\Delta x}\right) \quad (5)$$

where Θ is the angle (shown in Figure 18), Δy is the difference in pixels in the y direction (up/down) and Δx is the difference in pixels in the x direction (left/right) between the end and beginning of the crack. The angle Θ is measured relative to a horizontal line. For cracks to the left of the hole, this line begins at the end of the crack end. For cracks to the right of the hole, this line begins at the start of the crack. As such, positive Θ goes from lower left to upper right and negative Θ goes from upper left to lower right. In almost all cases the Right Side cracks have negative angles while the Left Side cracks have positive angles. The polar angle ϕ of the crack initiation point is also calculated. This is the angle around the hole center at which the crack begins (i.e. on the hole perimeter). This angle varies from 0° at the bottom of the hole; most cracks start in regions of $\phi = 70 - 110^\circ$ (right side) and $\phi = 250 - 290^\circ$ (left side). The angles for specimen 26 are shown in Table 4.

Specimen	Crack Label	Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
-26 (0.325 OHT x 1500K)	R1	-7.23	271.17
	R2	-7.71	94.67
	L1	7.99	280.22
	L2	8.44	109.01

Table 4. Crack angle details for specimen 26 (0.325 OHT x 1500K).

Figure 18. Crack angles calculations using hole quadrants for specimen 26.

Once a set of data was completed (i.e. crack length known for the selected cycle points), the crack length was linearly interpolated to estimate the number of cycles required for the crack to achieve a length of 1 mm (0.0394 in). In aerospace applications, a threshold length of approximately 2-5 mm is often denoted as “crack initiation,” representing the detectable length of a crack using certain methods and detail of investigation. In this study, the threshold length of 1 mm (0.0394 in) was used with subsequent analysis based upon the crack growth in terms of the number of cycles since 1

mm crack length was achieved. This provides improved uniformity to the data, separating out the often-random crack growth behavior in the 0-1 mm range, which is considered separately. It should be emphasized, however, that in this study, crack initiation always refers to the moment when the crack was first detected (at lengths generally much shorter than 1 mm) rather than when it achieved 1 mm length.

The 1 mm threshold cycle count is obtained for each crack. This is done in the current study by linearly interpolating between collected data points surrounding the desired 1 mm length.⁹ As such, there may be some variation between the predicted cycles at 1 mm length and the actual value in each experiment. The crack lengths versus cycles since 1 mm length are then plotted for each side of each specimen; the results for the left side of specimen 10 are shown in Figure 19. The trendline feature in Excel is then used to fit the data with a parabola of the form

$$L(x) = c_0 + c_1 x + c_2 x^2 \quad (6)$$

where x is the number of cycles since 1 mm crack length, c_0 is a constant term equal to 1.00 mm, and c_1 and c_2 are constants determined by Excel. The coefficients for each curve are tabulated; results for specimen 10 are shown in Table 5 along with the number of cycles at 1 mm crack length. The parabolic fit performed adequately for the results in this study; other appropriate curves could also have been chosen.

⁹ Ideally, determination of the moment of 1 mm crack length would be done by reviewing individual montages. This was done in this study due to time constraints.

Figure 19. Crack length versus cycles since cracks reached 1mm in length.

	L1	L2	L3
c2	-1.8370E-05	-1.6808E-05	-3.2867E-05
c1	2.5148E-02	3.3223E-02	4.7034E-02
c0	1	1	1
R ²	9.5192E-01	9.9308E-01	9.9201E-01
Apparent Cycles (K) at 1 mm Length	100.2	23.2	8.6

Table 5. Left side curve fit coefficients for specimen 10.

The curve fits in Table 5 predict crack length (a) versus cycles ($N - N_o$), where N_o is the number of cycles to 1 mm length. This curve can be differentiated to consider the crack growth rate da/dN as:

$$\frac{da}{dN} = \frac{da}{d(N - N_o)} \frac{d(N - N_o)}{dN} = \frac{da}{dx} = 2c_2x + c_1 \quad (7)$$

These can be plotted to assess whether the crack growth rate increasing or decreasing with crack length. For the AFML specimens, virtually all specimens showed a

decreasing rate of crack growth. This is shown for one specimen, 26, in Figure 20. For an aluminum specimen in the same geometry, da/dN would increase with cycles.

Figure 20. Crack growth rate vs. cycles since 1 mm crack length for specimen 26.

One last point of interest was analyzed for each crack; crack initiation and initial crack growth rate. A comprehensive list was compiled of the cycle count at initiation for each crack along with the interpolated cycles at 1 mm length. Because crack growth begins at 1mm (when a crack is assumed to be stable and “visible”) the growth rates da/dN from 0-1 mm were considered and graphed; these were calculated using the equation:

$$\frac{da}{dN} = \frac{1mm}{N_{1mm} - N_{init}} \quad (8)$$

Where N_{init} and N_{1mm} are the number of cycles (K) when the crack in question initiated and when it reached 1 mm, respectively. This is an average rate of growth. It is

reported in microns per thousand cycles. An example for specimen 10 is shown in Table

6. In general, there is a great deal of variation in the crack growth rates from 0 – 1 mm.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-10 (0.475 OHT x 750K)	L3	A	6	8.6	384.6
	R3	B	7.5	24.1	60.2
	L2	B	7.5	23.2	63.7
	L1	C	9	100.2	11.0
	R4	C	9	39.1	33.2
	R2	D	37.5	61.3	42.0
	R1	D	37.5	51	74.1

Table 6. Specimen 10 labels and crack initiation details.

An analysis as described above was performed for each specimen in this study.

Certain key findings based upon these results will be presented in the next chapter. The full experimental results for each specimen are presented in the various appendices to this study.

C. Stiffness Loss Analysis

One other approach to assess crack growth is to monitor changes in the stiffness of the specimen. Each specimen in this study was monitored by two extensometers; these measure deformation of the region within ± 12.7 mm (± 0.5 in) of the center of the hole. The MTS also monitors displacement of the lower head; this provides a measurement of the overall deformation of the specimen (as well as dimensional changes related to machine stiffness). The resulting data can be used to calculate specimen stiffness.

During the fast cycles (see Figure 11), the maximum and minimum force as well as the associated displacement and extensometer readings are obtained for each cycle.

These are written to a text file for subsequent analysis. Using this maximum and

minimum data, the specimen stiffness can be expressed as an apparent modulus¹⁰ using the equation

$$M_e = \frac{\Delta F}{A} \frac{1}{\Delta \epsilon} \quad (9)$$

where M_e is the apparent modulus, ΔF is the difference in maximum and minimum forces, A is the cross sectional area of the specimen and $\Delta \epsilon$ is the perceived change in specimen strain that occurs due to ΔF . This last term comes either from the extensometers (gage length 25.4 mm) or the overall machine displacement (specimen length from grip to grip). Using this approach, the apparent modulus can be calculated for each cycle throughout the experiment.¹¹

During the slow cycles (see Figure 11), the load-displacement-extensometer data is collected at many points throughout the cycle. This data can also be used to determine an apparent modulus of elasticity of the specimen. In this case, the entire data set for a single slow cycle is converted to stress-strain data and the modulus is the optimal value that fits the equation:

$$\sigma_i = \frac{F_i}{A} \quad ; \quad \epsilon_i = \frac{l_i}{l_0} \quad ; \quad \sigma(\epsilon) = E \epsilon \quad (10)$$

where F_i and l_i are the force and length (extensometer or specimen length from machine displacement) at each data point, respectively, A is the cross-sectional area of the specimen and l_0 is the appropriate initial gage length.

¹⁰ This is not a modulus of elasticity (i.e. a material property) as the presence of the hole affects the result. This value instead represents a measure of the stiffness of the specimen including the effect of the hole and any cracks that are present.

¹¹ The files written by LabVIEW contain an extremely large amount of data. This is because virtually all of the 500K – 2000K cycles performed result in a line of data. To reduce the data to a reasonable amount for analysis every other line in the file is deleted and then every 20 lines is averaged (using a MathCad document) into a single analysis point. The deletion of lines is necessitated by the maximum array size that MathCad can store. This leads to a manageable amount of data.

V. RESULTS

In this section, the results of fatigue testing and analysis of aluminum fiber metal laminates will be presented. This begins with an overview of the cracks observed for each specimen, the effect that multiple cracks on a specimen have upon the crack growth of an individual crack, and general patterns, such as crack angle, that are common to all specimens. The relationship between the crack growth results for various specimens are then considered. This leads to a demonstration that linear elastic fracture mechanics offers a method to consider crack growth in AFMLs. The effect of variations on the baseline specimens (jig ground holes, shot peened surfaces) are also considered. Stiffness loss methods are considered briefly and are demonstrated to perform poorly at characterizing crack growth. An example of x-ray tomography for crack detection on AFML and TiGr specimens is also presented.

A. Summary of Crack Count Data

A total of 25 AFML specimens were tested in fatigue. These included 16 baseline specimens, 5 specimens with holes finished via jig grinding (hole variation) and 4 specimens with shot peened surfaces (surface variation). These specimens were subjected to tension-tension fatigue with $R = 0.10$ and a maximum stress of 25.0%, 32.5%, 40.0%, 47.5% or 55.0% of the baseline OHT stress. Based on findings discussed previously, it was assumed that all specimens had a common OHT stress; specifically, shot peening is assumed to leave the OHT stress unchanged.

The specimens subjected to fatigue testing are listed in Table 7 along with the relevant test details. The processed montage images at the end of each experiment were considered and the number of cracks in each of 4 quadrants were tabulated (left side image, left half; left side, right half; right side, left half; right side, right half). In this list,

the “left half” means the half of the specimen to the left of the hole while “right half” means the opposite. The tabulated number of cracks is also listed in Table 7. These results indicate that the number of cracks tends to increase as stress level increases. Other than that, this table is provided primarily for reference value.

Specimen	Test Details			Left Side Cracks		Right Side Cracks		Total Crack Count
	Stress (% OHT)	Cycles (K)	Specimen Type	Left Half Crack Count	Right Half Crack Count	Left Half Crack Count	Right Half Crack Count	
24	0.250	2000	Standard	1	1	1	0	3
25	0.250	2000	Standard	1	0	0	0	1
16	0.325	1500	Standard	2	1	1	1	5
20	0.325	1500	Standard	1	1	1	1	4
26	0.325	1500	Standard	1	1	1	1	4
27	0.325	1500	Standard	1	1	1	1	4
8	0.400	1000	Standard	1	1	1	1	4
17	0.400	1000	Standard	1	2	1	2	6
18	0.400	1000	Standard	1	2	1	1	5
19	0.400	1000	Standard	1	1	1	1	4
10	0.475	750	Standard	2	1	2	2	7
11	0.475	750	Standard	2	1	2	1	6
12	0.475	750	Standard	2	1	2	1	6
13	0.475	750	Standard	1	1	2	2	6
7	0.550	500	Standard	2	2	2	1	7
23	0.550	500	Standard	2	1	2	2	7
37	0.325	1500	Jig Grind	1	1	1	2	5
39	0.325	1500	Jig Grind	1	1	1	1	4
29	0.475	750	Jig Grind	2	2	2	2	8
35	0.475	750	Jig Grind	2	1	1	1	5
36	0.475	750	Jig Grind	2	1	1	2	6
30	0.475	750	Shot Peen	2	0	2	1	5
31	0.475	750	Shot Peen	2	2	2	2	8
33	0.550	1000	Shot Peen	2	1	2	2	7
34	0.550	1000	Shot Peen	1	2	1	1	5

Table 7. Specimen stress levels, cycle count and crack count details

B. Effect of Neighboring Cracks

In this study, analysis will be performed on a selected set of cracks from various specimens. Given that there are generally multiple cracks on a given specimen, it is useful to first consider in what ways cracks influence one another (if at all). If the behavior of a given crack is dependent upon all other cracks on a specimen, the analysis is much more involved. Alternately, if each crack can be considered independently of its

neighbors, the analysis is greatly simplified and broader generalizations and predictions can be made.

Two types of crack interaction will be considered first: a) cracks on the opposite surfaces of a specimen (i.e. in different aluminum layers); and b) cracks on the same surface but on opposite sides of the hole. To consider this, one crack on each of three specimens with different combinations of cracks on opposite surfaces and sides of the hole were considered. All were tested at 40% OHT and each crack selected for consideration was the first to initiate (label A) per specimen. The cracks considered are specimen 17 L1, specimen 18 R1, and specimen 19 L2. The montage images for each specimen are shown in Figure 21. On each montage is a set of arrows going from the crack in question to the cracks on the opposite surface / same side of the hole and the same surface / opposite side of the hole. In terms of the crack count in these regions, the relationship between each of these three cracks and its neighbors is shown in Table 8.

Figure 21. Comparison between [A] cracks for 40% OHT specimens
(All three of these cracks are the only crack on their respective sides of the hole).

Specimen / Label of Crack Considered	Number of Cracks, Opposite Surface, Same Side of Hole	Number of Cracks, Same Surface, Opposite Side of Hole
17 R1	2	2
18 R1	2	1
19 L2	1	1

Table 8. Crack counts in regions neighboring particular cracks under consideration (each crack is among the first set of cracks to initiate, label [A])

It is clear that these three cracks capture several different combinations of possibilities in terms of the number of neighboring cracks. As such, if there were crack interaction effects, it would be reasonable to expect the rate of crack growth to differ markedly for the three. To assess this, the crack length versus cycles are plotted for these

three cracks in Figure 22. All three of these cracks grow at nearly the same rate; this indicates that the rate of crack growth is not dependent on the number of cracks on either the opposite surface of the specimen or on the opposite side of the hole. In order to consider this more fully, another set of three cracks on the same specimens was also considered. These were the second cracks to initiate on the specimens ([B] label); they are listed in Table 9 along with neighboring crack counts similar to Table 8. The resulting crack growth versus cycle count for each of the cracks is shown in Figure 23. Again, there is no discernible difference between the results. This further supports the argument that cracks are not affected by the number of cracks on either the opposite surface or opposite side of the hole.

Figure 22. Comparison between three [A] cracks tested at 40% OHT (the cycles at 1 mm length for each crack are listed in legend).

Specimen / Label of Crack Considered	Number of Cracks, Opposite Surface, Same Side of Hole	Number of Cracks, Same Surface, Opposite Side of Hole
17 L1	1	2
18 R2	2	1
19 L1	1	1

Table 9. Crack counts in regions neighboring particular cracks under consideration (second set of cracks to initiate, label [B])

Figure 23. Comparison between three [B] cracks tested at 40% OHT.

However, for multiple cracks existing on the same surface on the same side of the hole (e.g. cracks 17 R2 and 17 R3 in Figure 21), each crack can affect the other and the crack growth rates are often noticeably different. For example, refer to the left side of Specimen 10 (bottom image of montage) in Figure 16. There are two cracks to the left of the hole (10 L1 and 10 L2) and one crack to the right of the hole (10 L3). Crack 10 L1

initiates approximately 80K cycles after crack 10 L2, while cracks 10 L2 and 10 L3 initiated within 17K cycles of one another. The crack growth versus cycles was shown previously for the left side of specimen 10 in Figure 19. From this figure, it is clear that cracks 10 L3 and 10 L2 grow similarly but that 10 L2 has a markedly slower rate of crack growth. This can be explained by the close proximity of a second crack (10 L1) to 10 L2, which likely lowers the stresses / driving force to extend crack 10 L2 (i.e. each crack shields the other). Likewise, the rate of growth of 10 L1 is slower yet again, presumably due to the shielding it receives from its longer crack neighbor 10 L2. Thus, the presence of multiple cracks on the same surface on the same side of the hole can change the crack growth behavior significantly. As such, the presence of neighboring cracks on the same surface and same side of the hole should be considered when evaluating crack growth results.

C. Crack Initiation

One area of interest in the fatigue of AFMLs is the number of cycles at which cracks will initiate. In the context of this study, initiation is the moment when a crack is first detected by visual inspection. Ideally, there would be a strong, predictable relationship between the stress at the hole and the number of cycles required for crack initiation. However, this phenomenon is driven by many features, such as minute flaws in the region of interest, grain size and orientation in the aluminum layer, surface texture / roughness, etc. As such, it is reasonable to expect significant variation in the cycles to crack initiation. This expectation is borne out by the data attained in this study. For each specimen, the first crack to initiate was noted along with the number of cycles when the crack appeared (these values can be obtained from various tables in the Appendix). The average cycles to crack initiation along with the maximum and minimum cycle values

were calculated for each stress level and specimen variation; the results are listed in Table 10 and plotted against the stress level for each condition in Figure 24. Many of the results have relatively little variation in the cycles at first crack initiation (with the exception of the baseline specimens at 25.0% and 47.5% OHT). There is also a relatively clear trend between increasing stress level and decreasing cycles to crack initiation. However, it should be noted that this table only considers the first crack to initiate. Given specimen symmetry, it would be reasonable to expect crack initiation to occur in all four quadrants at relatively similar times (left / right side, left / right of hole). However, the other cracks generally occur at different cycle counts for reasons that are unclear. Further consideration of this data may provide additional insights into the crack initiation phenomenon.

Stress Level (OHT)	Cycles (K)	Specimen Details	Number of Specimens In Average	Average Cycles at Crack Initiation (K)	Maximum Cycles at Crack Initiation (K)	Minimum Cycles at Crack Initiation (K)
0.250	2000	Baseline	2	220.0	352.0	88.0
0.325	1500	Baseline	4	73.0	78.0	66.9
0.400	1000	Baseline	4	38.5	46.0	30.0
0.475	750	Baseline	4	23.3	45.0	6.0
0.550	500	Baseline	2	30.0	40.0	20.0
0.325	1500	Jig Grind	2	49.5	51.0	48.0
0.475	750	Jig Grind	3	26.9	36.0	22.1
0.475	750	Shot Peen	1	30.0	30.0	30.0
0.550	1000	Shot Peen	2	23.0	24.0	22.0

Table 10. Average cycles to first crack initiation for baseline, jig grind and shot peened specimens.

Figure 24. Average cycles to first crack initiation for baseline, jig grind and shot peened specimens vs OHT level.

The data in Table 10 also provides a method to consider the effect of different hole treatments. One reason that jig ground holes are included in this study as a variation is to ascertain whether this method of hole treatment / finishing provides a benefit relative to reaming (a much less complicated and more common hole finishing method). The cycles to crack initiation are similar or lower than those of the baseline specimens at similar stress levels. Based on these limited findings, it appears that jig ground holes offer no improvement (and are possibly worse) compared to reamed holes in terms of delaying crack initiation.

D. Crack Angles

One clear finding when considering the results of various specimens is the trend observed in terms of the angle at which the cracks grow. The PMC ply lay-up consists

solely of 0, ± 45 and 90 degree plies (see Figure 1). Adjacent to the left and right side aluminum layers is a +45 degree ply. For the right side (“bag side” or top of the panel), the fibers are in the direction shown in Figure 1. However, for the left side (“tool side or bottom of the panel), the ply appears to be a mirror image (as seen by the camera) and the fibers appear to travel in the -45 direction. To clarify this, Figure 25 shows the montage image for specimen 26 along with schematics indicating the orientation that the fibers immediately below aluminum layers would appear to have to the camera.

Figure 25. Ply lay-up behind aluminum sheets.

The orientation of the fibers in the ply below the aluminum layer appears to have an effect on the direction of the crack paths. The overall angle of each crack (measured from the end of the crack to its initiation point) was calculated for each crack (as angle Θ ; see Figure 18). The resulting angle correlates extremely well with the side on which they formed. Specifically, for cracks that occur on the right side, the crack path follows a negative direction (from upper left to lower right). Similarly, for cracks that occur on the

left side, the crack path follows a positive direction (from lower left to upper right).

These findings are true for specimen 26 in Figure 25 and hold for virtually all specimens tested. To demonstrate this, the angle of each crack was calculated based on the location of the crack tip at end of the experiment and the associated initiation point. The resulting values are listed in Table 11. The average right side crack angle was -6.06 degrees while the average left side angle was +7.78 degrees. Both had a relatively low coefficient of variation of 21%.

Specimen	Stress Level (OHT)	Cycles (K)	Specimen Type	Average Crack Angle Right Side (deg)	Average Crack Angle Left Side (deg)
-24	0.250	2000	Standard	-6.44	7.96
-25	0.250	2000	Standard		9.29
-16	0.325	1500	Standard	-7.45	7.63
-20	0.325	1500	Standard	-7.11	9.38
-26	0.325	1500	Standard	-7.47	8.21
-27	0.325	1500	Standard	-6.81	9.65
-08	0.400	1000	Standard	-6.37	8.31
-17	0.400	1000	Standard	-5.89	5.40
-18	0.400	1000	Standard	-7.54	5.77
-19	0.400	1000	Standard	-6.72	8.64
-10	0.475	750	Standard	-5.07	7.89
-11	0.475	750	Standard	-5.80	7.09
-12	0.475	750	Standard	-6.64	5.18
-13	0.475	750	Standard	-4.88	8.65
-07	0.550	500	Standard	-6.87	5.58
-23	0.550	500	Standard	-5.26	7.83
-37	0.325	1500	Jig Grind	-3.78	11.31
-39	0.325	1500	Jig Grind	-5.61	9.88
-29	0.475	750	Jig Grind	-2.92	8.17
-35	0.475	750	Jig Grind	-6.06	8.48
-36	0.475	750	Jig Grind	-4.98	7.92
-30	0.475	750	Shot Peen	-8.87	4.59
-31	0.475	750	Shot Peen		
-33	0.550	1000	Shot Peen	-4.73	7.36
-34	0.550	1000	Shot Peen	-6.02	6.55
Average				-6.06	7.78
CV				21.9%	21.0%

Table 11. Details of crack angles on left and right side of all fatigue specimens

E. Scale Factors and Reference Crack Growth Curve

Crack growth per cycle increases rapidly with increasing stress levels. This is demonstrated by five baseline specimens tested at five different stress levels (25.0%, 32.5%, 40.0%, 47.5% and 55.0% OHT). For each specimen, the first crack to initiate is presented. The crack growth versus cycles since 1 mm crack length are shown for each of the specimens in Figure 26; additional details for the specimens can be found in the Appendix in Figure 54, Figure 59, Figure 74, Figure 86, and Figure 92. Each crack in this analysis was the only crack on the associated surface and side of the hole; thus, interaction effects with neighboring cracks could be neglected. Clearly, the crack growth rates are related to the stress level of the test.

Figure 26. Crack length vs. number of fatigue cycles since 1 mm crack length for baseline specimens at 25.0%, 32.5%, 40.0%, 47.5% and 55.0% OHT stress levels.

The five curves in Figure 26 all share a fairly similar shape and can be collapsed into one another if the cycles since 1 mm crack growth are multiplied by an appropriately chosen scale factor A. Specifically, if the original data point is (X, L) where X is the cycles since 1 mm crack length and L is the crack length at that moment, the curves collapse when the data is plotted as (A X, L). In Figure 27, the data in Figure 26 is plotted using scale factors equal to 1.00, 1.60, 5.50, 6.80 and 8.50 for 25.0%, 32.5%, 40.0%, 47.5% and 55.0% stress levels, respectively. The specimen at 25.0% OHT has a Scale factor of 1.00, meaning that this is the reference stress level. These scale factors demonstrate that to achieve the same crack length of the specimen tested at 25.0% OHT stress (reference) after a certain number of cycles, specimens tested at another OHT stress level would only have to be cycled for $1 / A$ time as many cycles. The curve fit and associated coefficients shown in Figure 27 represent the best fit of the entire scaled data set. This curve is referred to as the reference crack growth curve; combined with an appropriate Scale factor A, it can be used to predict crack growth at any stress level. All scale factors presented in this study were determined by visual inspection.

Figure 27. Scaled crack growth data and curve fit for five baseline specimens.

The results in Figure 27 are based upon 5 of the 25 fatigue specimens considered in this study. The remaining specimens were considered in order to determine the optimal scale factor to shift the data to the reference crack growth curve shown in Figure 27. For each specimen, the first crack to initiate is considered. The resulting shifted data sets for the baseline specimens are shown in Figure 28, Figure 29, Figure 30, Figure 31, and Figure 32 for 25.0%, 32.5%, 40.0%, 47.5% and 55.0% OHT stress levels, respectively. The resulting shifted data for the specimen with jig ground holes are shown in Figure 33 and Figure 34 for 32.5% and 47.5% OHT stress levels, respectively. Finally, the resulting shifted data for the specimens with shot peened surfaces are shown in Figure 35 and Figure 36 for 47.5% and 55.0% OHT stress levels, respectively. The scale factors associated with each shifted data set are summarized in Table 12. Given the similarity of

the behavior of specimens at different stress levels and specimen variations, it is apparent that there is an underlying phenomenon relating these results. This is the subject of the next section.

Figure 28. Scaled crack growth data and reference for 25.0% OHT baseline specimens.

Figure 29. Scaled crack growth data and reference for 32.5% OHT baseline specimens.

Figure 30. Scaled crack growth data and reference for 40.0% OHT baseline specimens.

Figure 31. Scaled crack growth data and reference for 47.5% OHT baseline specimens.

Figure 32. Scaled crack growth data and reference for 55.0% OHT baseline specimens.

Figure 33. Scaled crack growth data and reference for 32.5% OHT jig ground specimens.

Figure 34. Scaled crack growth data and reference for 47.5% OHT jig ground specimens.

Figure 35. Scaled crack growth data and reference for 47.5% OHT shot peened specimens.

Figure 36. Scaled crack growth data and reference for 55.0% OHT shot peened specimens.

Specimen	Stress Level (OHT)	Cycles (K)	Specimen Type	Crack Label	Scale Factor
-24	0.250	2000	Standard	L2	1.00
-25	0.250	2000	Standard	L1	1.00
-16	0.325	1500	Standard	R2	1.90
-20	0.325	1500	Standard	L1	1.60
-26	0.325	1500	Standard	L1	2.10
-27	0.325	1500	Standard	L1	2.00
-08	0.400	1000	Standard	L1	4.40
-17	0.400	1000	Standard	R1	4.80
-18	0.400	1000	Standard	R1	5.50
-19	0.400	1000	Standard	L2	4.50
-10	0.475	750	Standard	L3	9.00
-11	0.475	750	Standard	L2	6.50
-12	0.475	750	Standard	R3	6.80
-13	0.475	750	Standard	L2	7.20
-07	0.550	500	Standard	R3	8.50
-23	0.550	500	Standard	L3	9.00
-37	0.325	1500	Jig Grind	L2	2.10
-39	0.325	1500	Jig Grind	L1	1.90
-29	0.475	750	Jig Grind	R1	6.00
-35	0.475	750	Jig Grind	L3	5.70
-36	0.475	750	Jig Grind	L3	6.70
-30	0.475	750	Shot Peen	L2	3.10
-31	0.475	750	Shot Peen		
-33	0.550	1000	Shot Peen	L3	4.00
-34	0.550	1000	Shot Peen	L1	4.20

Table 12. Scale factor for each crack for various OHT stress level and variations

F. Linear Elastic Fracture Mechanics

The findings in the previous section can be explained by linear elastic fracture mechanics (Anderson, 1991).¹² This subject deals with crack growth in linear elastic solids (such as the aluminum layers on the outer surfaces of the AFMLs in this study). In fracture mechanics, the rate of crack growth per fatigue cycle (da/dN) can be related to the stress intensity factor, K , present at the crack tip. The key quantity for fatigue is the difference between the maximum stress intensity factor (K_{max}) and minimum stress intensity factor (K_{min}) during the fatigue cycle ($\Delta K = K_{max} - K_{min}$) and the stress intensity

¹² The equations in this section were developed by Dr. Roger Bradshaw following consultation with Dr. Matthew Miller of the Boeing Company.

ratio $R = K_{\min}/K_{\max}$. The relationship between da/dN and ΔK for ductile metals is provided by a curve of the form shown in Figure 37 (Anderson, 1991).

Figure 37. Typical fatigue crack growth behavior in ductile metals (Anderson, 1991).

The linear region of the log-log plot of Figure 37 is described by

$$\frac{da}{dN} = C(\Delta K)^m \quad (11)$$

where C and m are material constants. The stress intensity factor, K , is described by

$$K = \sigma_0 Y \sqrt{\pi a} \quad (12)$$

where Y is the shape factor for the crack at the moment of consideration. The shape factor can encompass many issues related to the crack (length, path, etc.) and is the essential unknown necessary to characterize crack growth. In this section, it is assumed that the shape factor depends solely upon the length of the crack. As such, it can be written as a function of crack length a , leading to the simplified stress intensity factor equation:

$$K = \sigma_0 Y(a) \sqrt{\pi a} \quad (13)$$

The change in stress intensity factor throughout the cycle (ΔK) for $R = 0.10$ can be written as:

$$\Delta K = K_{\max} - K_{\min} = (\sigma_0 Y(a) \sqrt{\pi a}) - (0.10 \sigma_0 Y(a) \sqrt{\pi a}) = 0.90 \sigma_0 Y(a) \sqrt{\pi a} \quad (14)$$

where σ_0 is the maximum stress during the fatigue cycle. With this, the crack growth rate da/dN at any crack length a can be written as

$$\frac{da}{dN} = C (0.90 \sigma_0^{\max} Y(a) \sqrt{\pi a})^m \quad (15)$$

In this expression, the material properties C and m as well as the stress level $\sigma_0^{\max}$ are known; only the shape factor $Y(a)$ for a certain crack length a is unknown.

Denote the number of fatigue cycles at a certain point in the experiment by the variable ζ . Since the number of fatigue cycles and the crack length a both increase monotonically throughout the experiment, there is a one-to-one relationship between these two items (i.e. one value of crack length a is uniquely related to the number of cycles ζ at that length and vice versa). As such, the crack length can be expressed as a function in terms of the number of fatigue cycles as $a(\zeta)$. With this understanding, the rate of crack growth can be expressed in terms of the number of cycles as:

$$\frac{da}{d\zeta} = C (0.90 \sigma_0^{\max} Y[a(\zeta)] \sqrt{\pi a(\zeta)})^m \quad (16)$$

which can be further simplified as

$$\frac{da}{d\zeta} = \beta (\sigma_0^{\max})^m [Y[a(\zeta)] \sqrt{a(\zeta)}]^m \quad ; \quad \beta = C (0.90 \sqrt{\pi})^m \quad (17)$$

where β is a constant that depends only on material properties.

It should be emphasized at this point that the function $a(\zeta)$ is likely not known. However, Eq. 17 provides a method for determining it if the shape factor function $Y(a)$

is known for all crack lengths. Specifically, Eq. 17 can be integrated between two cycle limits (0 to N) to obtain:

$$a(N) = (\sigma_0^{\max})^m \beta \int_0^N \left[Y[a(\zeta)] \sqrt{a(\zeta)} \right]^m d\zeta \quad (18)$$

This is an integral equation of the second kind, meaning that the unknown function to be determined (crack length a) exists both inside and outside of the integral. There are a variety of methods that can be used to numerically solve this type of equation; for example, it can be considered as an initial value problem using various differential equation methods to obtain the solution for a throughout the range from 0 to N cycles. The method to be used is not important to the derivation that follows and will not be discussed further.

The derivation above can be similarly performed at a different stress level with similar results. Specifically, consider a fatigue test performed at a reference stress level $\sigma_{0-ref}^{\max}$. The crack length function $\tilde{a}$ at this stress level can be written as in terms of the number of cycles ξ at the reference stress level as:

$$\frac{d\tilde{a}}{d\xi} = \beta (\sigma_{0-ref}^{\max})^m \left[Y[\tilde{a}(\xi)] \sqrt{\tilde{a}(\xi)} \right]^m \quad (19)$$

where β is as before. This could be integrated and solved as before to find:

$$\tilde{a}(\tilde{N}) = (\sigma_{0-ref}^{\max})^m \beta \int_0^{\tilde{N}} \left[Y[\tilde{a}(\zeta)] \sqrt{\tilde{a}(\zeta)} \right]^m d\zeta \quad (20)$$

where $\tilde{N}$ is the number of cycles under consideration at the reference stress level.

There is a relationship between the crack length functions for a general stress level (a from Eq. 18) and the reference stress level ($\tilde{a}$ from Eq. 20). Specifically, N

cycles at stress $\sigma_0^{\max}$ leads to an equivalent crack length after $\tilde{N}$ cycles at $\sigma_{0-ref}^{\max}$ when

N and $\tilde{N}$ satisfy the equation:

$$\tilde{N} = \left(\frac{\sigma_0^{\max}}{\sigma_{0-ref}^{\max}} \right)^m N \quad (21)$$

The correctness of this relationship will be demonstrated by showing an equivalence between Eqs. 18 and 20 when it is employed. First, since Eq. 21 must hold for any value of N , this implies that any cycle count ξ at the reference stress level $\sigma_{0-ref}^{\max}$ can be related to the cycle count ζ at $\sigma_0^{\max}$. Furthermore, since the term in parentheses in Eq. 21 is constant throughout each experiment, this expression can be differentiated to find:

$$\xi = \left(\frac{\sigma_0^{\max}}{\sigma_{0-ref}^{\max}} \right)^m \zeta \rightarrow \frac{d\xi}{d\zeta} = \left(\frac{\sigma_0^{\max}}{\sigma_{0-ref}^{\max}} \right)^m \quad (22)$$

Now return to Eq. 17, which expresses the crack growth rate at $\sigma_0^{\max}$ in terms of the cycles at that stress level (ζ). Using the chain rule, this can be recast in terms of the change in crack length per the number of cycles at the reference stress level as

$$\frac{da}{d\zeta} = \frac{da}{d\xi} \frac{d\xi}{d\zeta} = \frac{da}{d\xi} \left(\frac{\sigma_0^{\max}}{\sigma_{0-ref}^{\max}} \right)^m = \beta (\sigma_{0-ref}^{\max})^m [Y[a(\zeta)]\sqrt{a(\zeta)}]^m \quad (23)$$

Clearing out the stress terms leads to:

$$\frac{da}{d\xi} = \beta (\sigma_{0-ref}^{\max})^m [Y[a(\zeta)]\sqrt{a(\zeta)}]^m \quad (24)$$

This expression can be integrated from 0 to $\tilde{N}$ cycles to find:

$$a(\tilde{N}) = (\sigma_{0-ref}^{\max})^m \int_0^{\tilde{N}} [Y[a(\zeta)]\sqrt{a(\zeta)}]^m d\zeta \quad (25)$$

This expression is clearly the same as that in Eq. 20, which demonstrates that the relationship between the cycle counts at different stress levels in Eq. 21 is shown to be

correct. For two different stress levels when the numbers of cycles ($N, \tilde{N}$) are related by Eq. 21, equal crack lengths will be obtained as:

$$a(N) = \tilde{a}(\tilde{N}) \quad (26)$$

The term in parentheses in Eq. 21 is referred to in this work as the scale factor. Thus, a relationship between the scale factors and the ratio of the test and reference stress levels has been established. The scale factors obtained previously for all 16 baseline specimens (see Table 12) were plotted versus stress level as shown in Figure 38; a power law curve fit is shown of the form

$$y = Cx^m \quad (21)$$

where C is a constant, x is the OHT stress ratio and m is the power. The fit is adequate ($m = 3.044$) but clearly misses the 55.0% specimens. A similar plot with the 55.0% OHT stress level values excluded is shown in Figure 39; the fit is much better ($m = 3.294$). The value of m improves further if the 25% specimens are excluded; this results is shown in Figure 40 ($m=3.597$).

Figure 38. Scale factors versus stress level for all baseline specimens.

Figure 39. Scale factors versus stress level for 25.0% - 47.5% OHT stress baseline specimens (55.0% OHT stress specimens).

Figure 40. Scale factors versus stress level for 32.5% - 47.5% OHT stress baseline specimens (excludes 25.0% and 55.0% OHT stress specimens).

The power values (3.0 – 3.6) obtained above are consistent with 2024-T3 series aluminum alloy values obtained by The Boeing Company ($m = 3.7$). The exclusion of the extrema specimens (55.0% OHT stress) leads to better agreement; this indicates that these specimens may lay outside the linear portion of the $da/dN - \Delta K$ relationship (see Figure 37) or that other phenomenon such as multiple cracks / side cracks are affecting the results for the 55.0% OHT specimens. Regardless, experimentally obtained values of m in the range of 3.0 – 3.6 are quite satisfactory.

These findings indicate that linear elastic fracture mechanics can be used to predict the crack growth for AFML specimens. The chief item that is unknown is the shape factor $Y(a)$; this can be obtained by an appropriate finite element model or determined from the experimental data. Further consideration of fracture mechanics with the data obtained in this study remains for a future project.

G. Effect of Shot Peening on Crack Growth

The effects of hole quality and surface were studied in nine of the OHT specimens. These specimens were tested as shown in Table 13.

OHT Level	Cycles (k)	Specimen	Treatment
0.475	750	-29, -35, -36	Jig Grind
0.325	1500	37, -39	Jig Grind
0.475	750	-30, -31	Shot Peened
0.550	1000	-33, -34	Shot Peened

Table 13. Test specifications for hole/material variation specimens.

In fatigue testing, the cracks in the shot peened specimens are barely visible. Because the tests conducted at 47.5% OHT at the same cycle lengths as the reamed specimens produces such faint cracks the tests completed at 55% OHT were cycled for double the cycles used previously. For the 47.5% shot peened specimens only specimen 30 was analyzed. The cracks at 47.5% OHT are not visible in the find edge montage, found in the Appendix. For specimen 30 the original color pictures were imported into Microsoft Paint, manually touched up and then analyzed. This process is not as dependable as the crack analysis for other OHT level specimens. Figure 41 shows that at 55% OHT the reamed specimen cracks grow at a much faster rate than the shot peened cracks. At the end of the tests the crack lengths are very close to one another but the shot peened specimens required twice the amount of cycles to reach this final length. This result is also evident in the scale factors obtained previously (Table 12); these are plotted in Figure 42. It is clear that the shot peened specimens have crack growth rates that are much lower than their baseline counterparts at an identical stress level. Another way to consider the same data is that the shot peened specimens act similar to the baseline specimens fatigued at a stress level that is 10-15% OHT below their actual stress level (in

Figure 42 the 55% OHT specimen at similar to 40% OHT baseline specimen, approximately).

Figure 41. First crack to initiate for shot peened, 33 and 34, and reamed, 7 and 23, specimens vs. cycle count.

Figure 42. Shot peened scale factors vs baseline.

H. Effect of Jig Ground Holes on Crack Growth

The results for the jig ground specimens at 32.5% OHT and 47.5% OHT shown in Figure 43 and Figure 44, respectively; these are compared to the baseline (reamed) specimens. The specimens with the jig ground holes do not demonstrate a noticeable difference when compared to the baseline specimens. This is reasonable since jig grinding improves the quality of the hole but not the material behavior away from the hole; thus, jig grinding may modify the crack initiation characteristics (i.e. delay crack initiation) but not the rate of growth once a crack is initiated. These results can also be considered in terms of the scale factors obtained previously (Table 12); these are plotted in Figure 45. The similarity to the baseline values is another indication that jig grinding does not change the crack growth behavior.

Figure 43. Crack growth comparison at 32.5% for Reamed and Jig Grind Specimen.

Figure 44. Crack growth comparison at 47.5% for Reamed and Jig Grind Specimen.

Figure 45. Jig grind scale factors vs baseline.

I. Stiffness Loss

The effective modulus was calculated as described in Chapter IV. Using the processed data for the extensometers the calculated modulus¹³ was plotted versus the cycle count. For the fast cycle data of specimen 07, tested at 55.0% OHT for 500K cycles the extensometer 1, extensometers 2 and averaged extensometer data was plotted, Figure 46, Figure 47, Figure 48 respectively. These plots show the stiffness loss of the specimen. However, there is not an exact point to pinpoint the time of crack initiation.

¹³ The stiffness was normalized as $\sigma/\sigma_{\text{initial}}$ for proprietary reasons.

Figure 46. Effective modulus from extensometer 1 vs cycles for specimen 07, 55.0% OHT x 500K cycles (fast cycle data).

Figure 47. Effective modulus from extensometer 2 vs cycles for specimen 07, 55.0% OHT x 500K cycles (fast cycle data).

Figure 48. Effective modulus from average of extensometer1 and 2 vs cycles for specimen 07, 55.0% OHT x 500K cycles (fast cycle data).

For the slow cycles the stiffness of specimen 07 was calculated for extensometer 1, extensometer 2 and the head displacement, Figure 49 and Figure 50. This data is similar to the fast cycle data, demonstrating the decrease in stiffness of the specimen but is unable to identify the exact initiation cycle counts and crack lengths. A MathCad sheet was written to fit Eq. (10) as described in Chapter IV. The calculated slopes are plotted as normalized stiffness.

Figure 49. Effective modulus from extensometer1 and 2 vs cycles for specimen 07, 55.0% OHT x 500K cycles (slow cycle data).

Figure 50. Effective modulus from head displacement vs cycles for specimen 07, 55.0% OHT x 500K cycles (slow cycle data).

This data is very noisy due to several factors including the quality of the data acquisition card, the positioning of the extensometers and the high rate of the fast cycles, 7.5 Hz. A moving average was added to lessen the noise. The stiffness appears to have decreased over the 500K cycles due to cracking but there is not clear point in which each cracks initiates. The stiffness plots for several different stress levels were compared with no difference in results. The stiffness loss method for crack analysis needs future refinement in order to be used to characterize crack growth data.

J. X-ray Tomography

The visual inspection methods discussed in this thesis lead to outstanding crack characterization throughout the fatigue experiment. However, these methods are only suitable for metal layers on the outer surface of the laminate. For interior metal layers, alternative methods must be considered. One approach is to use x-rays to investigate the interior layers. The micro computed tomography (micro-CT) system at the University of Louisville (see Figure 51) was used in preliminary investigations to demonstrate the efficacy of this technique.¹⁴ This system permits the x-ray source and collector to focus on a very small region, leading to images with very fine resolution. Tests were performed during June-July, 2004 on TiGr specimens previously cracked in a fatigue study performed by John Osborne. This material had 3 titanium layers (two surface, one at mid plane) with 16 PMC plies. One resulting image is shown in Figure 52. This is a close-up image of the left side of the hole taken at an angle to the specimen; thus, each layer of the foil appears at a different location. The x-ray image indicates cracks in all three layers, including the middle layer that is not visible.

¹⁴ The x-ray images presented in this study were performed by Mr. Seid Waddell with input and assistance provided by Dr. Bill Hnat.

Figure 51. Micro-CT x-ray system at University of Louisville (image courtesy of Dr. Bill Hnat)

Figure 52. Image of a TiGr specimen as obtained by the micro-CT system

The micro-CT system was also used to investigate cracks in the AFML specimens used in the current study; one associated image for specimen 26 is shown in Figure 53. The cracks are clearly visible. It is reasonable to conclude that cracks could be similarly observed for interior aluminum layers if they were present. Further refinement of the method to investigate individual cracks (i.e. focusing only on one side of the hole at a higher magnification) and optimization of the imaging settings should also lead to further improvement of crack characterization. It is also likely that cracks would be more visible if the specimen was placed under load when the image is captured (as is done in this study when the visual images are captured). Based on these preliminary assessments, it appears that x-ray methods will lead to successful crack characterization for both exterior and interior layers.

Figure 53. Image of AFML specimen 26 as obtained by the micro-CT system (image contrast adjustments have been made to highlight cracks)

VI. CONCLUSIONS

Fatigue tests were performed on AFML specimens at a variety of stress levels with various hole and surface treatments. The fiber bridging benefits of the AFML were clearly demonstrated in terms of slowing rates of crack growth as crack length increases (the opposite of what would be found for an identical specimen made from a ductile metal). Visual inspection using an automated edge detection method was the most valuable means of analysis for this project. The only test for which this approach was not as useful was the shot peened specimens at a lower OHT level. For these specimens cracks were faint and difficult to detect visually; manual inspection of the original images was required. Stiffness loss monitoring was also performed. However, the results proved to be noisy with no clear indications of crack initiation but did give some indication of stiffness loss of the specimen. A more effective means of mounting the extensometers while allowing the digital images to be captured should be considered in future research.

Several important characteristics were identified and studied for AFML crack initiation and growth. A clear relationship between the crack length versus cycle count was established for specimens across widely different stress levels, hole treatment and surface preparation. This relationship was explained using linear elastic fracture mechanics; this demonstrates that this method is suitable for general AFML fatigue predictions once underlying functions are known. The effect of shot peening was demonstrated to reduce crack growth rates, highlighting one approach to mitigating crack growth in outer aluminum layers for which shot peening is practical. Crack initiation followed the expected trend, with higher stress levels causing cracks to appear after fewer cycles. Jig ground holes (as opposed to reamed holes used in the baseline specimens) do not lead to improvement in terms of crack initiation. The ply lay-up directly beneath the

aluminum layer was demonstrated to have a strong effect on the angle at which cracks grow. This relationship should be taken into consideration when fabricating AFML panels/structure.

This research project demonstrated that fatigue testing coupled with visual inspection methods can be used to effectively assess the crack initiation and growth behavior of aluminum fiber metal laminates. This method can be used in future studies in which the metal layers are solely on the outside of the laminate. For laminates with internal layers, alternate methods of crack detection / characterization such as x-ray tomography or DC potential drop methods need to be considered.

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VIII. APPENDIX

This section contains full documentation of the details for each specimen. A montage showing the Right Side and Left Side images at the end of the fatigue test begins each specimen summary. Each crack is labeled with a letter and number. The numbers indicate position on the left or right side while the letters indicate the order of crack appearance (details can be found in Chapter IV section B). Following each montage is a table containing the crack initiation summary containing the number cycles to crack initiation, estimated number of cycles to 1 mm crack length and apparent rate of crack growth from 0 – 1 mm length. A graph of the left side and right side crack lengths vs. cycles since cracks reached 1 mm length follows. The left and right side crack lengths and corresponding cycle counts are shown in tables along with the curve fits coefficients for each crack. Finally the overall crack angle (Θ) and polar angle at the crack initiation point (ϕ) are provided. Each OHT level is represented and described in the appropriate heading.

A. 25% OHT Reamed Specimens

Figure 54. Specimen 24 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-24	L2	A	88	204.3	8.6
(0.250 OHT	R1	B	176	206.2	33.1
x 2000K)	L1	C	228	284.9	17.6

Table 14. Specimen 24 crack labels and initiation summary.

Figure 55. Specimen 24 left side crack growth since 1 mm vs. cycle count.

Figure 56. Specimen 24 right side crack growth since 1 mm vs. cycle count.

L1 (284.9K)			L2 (204.3K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
1715.1	0.3850	9.78	1795.7	0.3840	9.75
1603.1	0.3790	9.63	1683.7	0.3744	9.51
1491.1	0.3487	8.86	1571.7	0.3470	8.81
1379.1	0.3058	7.77	1459.7	0.3041	7.72
1267.1	0.3058	7.77	1347.7	0.2981	7.57
1155.1	0.2991	7.60	1235.7	0.2890	7.34
1043.1	0.2711	6.89	1123.7	0.2765	7.02
931.1	0.2586	6.57	1011.7	0.2674	6.79
819.1	0.2405	6.11	899.7	0.2424	6.16
707.1	0.2220	5.64	787.7	0.2270	5.76
595.1	0.2008	5.10	675.7	0.2115	5.37
483.1	0.1758	4.47	563.7	0.1923	4.89
371.1	0.1516	3.85	451.7	0.1742	4.42
259.1	0.1486	3.77	339.7	0.1527	3.88
147.1	0.1091	2.77	227.7	0.1086	2.76
35.1	0.0572	1.45	115.7	0.1056	2.68
0.0	0.0394	1.00	75.7	0.0835	2.12
			23.7	0.0519	1.32
			0.0	0.0394	1.00

Table 15. Specimen 24 left side crack growth details.

	L1	L2
c2	-1.5624E-06	-1.4795E-06
c1	7.5880E-03	7.2525E-03
c0	1	1
R ²	9.7729E-01	9.7501E-01
Apparent Cycles (K) at 1 mm Length	284.9	204.3

Table 16. Specimen 24 left side crack growth curve fit coefficients.

R1 (206.2K)		
Cycles (K)	L (inches)	L (mm)
1793.8	0.3808	9.67
1681.8	0.3626	9.21
1569.8	0.3472	8.82
1457.8	0.3381	8.59
1345.8	0.3313	8.42
1233.8	0.3004	7.63
1121.8	0.2883	7.32
1009.8	0.2762	7.02
897.8	0.2518	6.39
785.8	0.2363	6.00
673.8	0.2149	5.46
561.8	0.1906	4.84
449.8	0.1876	4.77
337.8	0.1543	3.92
225.8	0.1388	3.53
113.8	0.0925	2.35
73.8	0.0773	1.96
21.8	0.0678	1.72
0.0	0.0394	1.00

Table 17. Specimen 24 right side crack growth details.

R1	
c2	-1.8787E-06
c1	7.9924E-03
c0	1
R ²	9.8279E-01
Apparent Cycles (K) at 1 mm Length	206.2

Table 18. Specimen 24 right side crack growth curve fit coefficients

		Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
Specimen	Crack Label		
-24 (0.250 OHT x 2000K)	R1	-6.44	268.64
	L1	7.59	286.39
	L2	8.33	89.33

Table 19. Crack angle details for specimen 24.

Figure 57. Specimen 25 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-25	L1	A	352	409.4	17.4
(0.250 OHT x 2000K)					

Table 20. Specimen 25 crack labels and initiation summary.

Figure 58. Specimen 25 left side crack growth since 1 mm vs. cycle count.

L1 (409.4K)		
Cycles (K)	L (inches)	L (mm)
1590.6	0.3688	9.37
1478.6	0.3420	8.69
1366.6	0.3189	8.10
1254.6	0.2929	7.44
1142.6	0.2862	7.27
1030.6	0.2621	6.66
918.6	0.2523	6.41
806.6	0.2208	5.61
694.6	0.2019	5.13
582.6	0.1785	4.53
470.6	0.1542	3.92
358.6	0.1458	3.70
246.6	0.1224	3.11
134.6	0.0981	2.49
22.6	0.0549	1.39
0.0	0.0394	1.00

Table 21. Specimen 25 left side crack growth details

L1	
c2	-1.1307E-06
c1	6.8299E-03
c0	1
R ²	9.8820E-01
Apparent Cycles (K) at 1 mm Length	409.4

Table 22. Specimen 25 left side crack growth curve fit coefficients.

Specimen	Crack Label	Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
-25	L1	9.29	271.15
(0.250 OHT x 2000K)			

Table 23. Crack angle details for specimen 25.

B. 32.5% OHT Reamed Specimens

170-16 RIGHT SIDE

170-16 LEFT SIDE

Figure 59. Specimen 16 montage with crack labels.

Specimen	Crack Label	Crack Label	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-16 (0.325 OHT x 1500K)	R1	A	78	118	25.0
	R2	B	84	99.4	64.9
	L2	C	114	147	30.3
	L3	D	144	157.9	71.9
	L1	E	150	194.6	22.4

Table 24. Specimen 16 crack labels and initiation summary.

Figure 60. Specimen 16 left side crack growth since 1 mm vs. cycle count.

Figure 61. Specimen 16 right side crack growth since 1 mm vs. cycle count.

L1 (194.6K)			L2 (147K)			L3 (157.9K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
1305.4	0.3054	7.76	1353.0	0.4886	12.41	1342.1	0.4265	10.83
1215.4	0.3026	7.69	1263.0	0.4274	10.86	1252.1	0.4126	10.48
1125.4	0.2661	6.76	1173.0	0.4071	10.34	1162.1	0.3803	9.66
1035.4	0.2367	6.01	1083.0	0.3764	9.56	1072.1	0.3691	9.38
945.4	0.2212	5.62	993.0	0.3553	9.03	982.1	0.3522	8.95
855.4	0.2170	5.51	903.0	0.3164	8.04	892.1	0.3097	7.87
765.4	0.2126	5.40	813.0	0.3022	7.68	802.1	0.2985	7.58
675.4	0.1929	4.90	723.0	0.2991	7.60	712.1	0.2665	6.77
585.4	0.1642	4.17	633.0	0.2709	6.88	622.1	0.2568	6.52
495.4	0.1559	3.96	543.0	0.2556	6.49	532.1	0.2183	5.54
405.4	0.1503	3.82	453.0	0.2291	5.82	442.1	0.2152	5.47
225.4	0.1464	3.72	273.0	0.1817	4.62	262.1	0.1760	4.47
135.4	0.1155	2.93	183.0	0.1648	4.19	172.1	0.1591	4.04
45.4	0.0794	2.02	93.0	0.1225	3.11	82.1	0.1103	2.80
0.0	0.0394	1.00	3.0	0.0569	1.44	0.0	0.0394	1.00
			0.0	0.0394	1.00			

Table 25. Specimen 16 left side crack growth details

	L1	L2	L3
c2	-1.5252E-06	-2.4062E-06	-2.6214E-06
c1	6.9072E-03	1.0890E-02	1.0628E-02
c0	1	1	1
R ²	9.1762E-01	9.6039E-01	9.6341E-01
Apparent Cycles (K) at 1 mm Length	194.6	147.0	157.9

Table 26. Specimen 16 left side crack growth curve fit coefficients.

R1 (118K)			R2 (99.4K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
1382.0	0.4725	12.00	1400.6	0.4597	11.68
1292.0	0.4356	11.06	1310.6	0.4395	11.16
1202.0	0.4285	10.89	1220.6	0.4096	10.40
1112.0	0.4099	10.41	1130.6	0.4010	10.19
1022.0	0.3759	9.55	1040.6	0.3698	9.39
932.0	0.3620	9.20	950.6	0.3628	9.21
842.0	0.3503	8.90	860.6	0.3356	8.52
752.0	0.3277	8.32	770.6	0.3155	8.01
662.0	0.2877	7.31	680.6	0.2809	7.13
572.0	0.2735	6.95	590.6	0.2752	6.99
482.0	0.2618	6.65	500.6	0.2510	6.37
302.0	0.2133	5.42	320.6	0.2111	5.36
212.0	0.1923	4.88	230.6	0.1783	4.53
122.0	0.1569	3.99	140.6	0.1555	3.95
32.0	0.0994	2.53	50.6	0.0930	2.36
26.0	0.0891	2.26	44.6	0.0814	2.07
0.0	0.0394	1.00	17.6	0.0725	1.84
			14.6	0.0769	1.95
			0.0	0.0394	1.00

Table 27. Specimen 16 right side crack growth details

	R1	R2
c2	-4.1460E-06	-3.6533E-06
c1	1.3153E-02	1.2325E-02
c0	1	1
R ²	9.5452E-01	9.7204E-01
Apparent Cycles (K) at 1 mm Length	118.0	99.4

Table 28. Specimen 16 right side crack growth curve fit coefficients.

Specimen	Crack Label	Crack Initiation	
		Overall Crack Angle (deg)	Point Angle (deg)
-16 (0.325 OHT x 1500K)	R1	-7.45	276.78
	R2	-7.45	93.09
	L1	7.19	254.98
	L2	7.61	293.98
	L3	8.10	103.30

Table 29. Crack angle details for specimen 16.

170-26 RIGHT SIDE

① B

② C

170-26 LEFT SIDE

① A

② D

Figure 62. Specimen 26 montage with crack labels.

Specimen	Crack Label	Crack Label	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-26 (0.325 OHT x 1500K)	L1	A	66.9	88.7	45.9
	R1	B	72	137.2	15.3
	R2	C	174	295.7	8.2
	L2	D	378	480.4	9.8

Table 30. Specimen 26 crack labels and initiation summary.

Figure 63. Specimen 26 left side crack growth since 1 mm vs. cycle count.

Figure 64. Specimen 26 right side crack growth since 1 mm vs. cycle count.

L1 (88.7K)			L2 (480.4K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
1411.3	0.5222	13.26	1019.6	0.4299	10.92
1360.3	0.5136	13.05	968.6	0.3906	9.92
1309.3	0.5021	12.75	917.6	0.3898	9.90
1258.3	0.4902	12.45	866.6	0.3813	9.68
1207.3	0.4699	11.94	815.6	0.3555	9.03
1156.3	0.4348	11.04	764.6	0.3377	8.58
1105.3	0.4297	10.91	713.6	0.3324	8.44
1054.3	0.4143	10.52	662.6	0.2976	7.56
1003.3	0.4049	10.29	611.6	0.2927	7.43
952.3	0.3885	9.87	560.6	0.2701	6.86
901.3	0.3715	9.44	509.6	0.2599	6.60
850.3	0.3602	9.15	458.6	0.2556	6.49
799.3	0.3576	9.08	407.6	0.2335	5.93
748.3	0.3388	8.61	356.6	0.2061	5.23
697.3	0.3319	8.43	305.6	0.1959	4.98
646.3	0.3300	8.38	254.6	0.1755	4.46
595.3	0.2932	7.45	203.6	0.1501	3.81
544.3	0.2720	6.91	152.6	0.1385	3.52
493.3	0.2355	5.98	101.6	0.1174	2.98
442.3	0.2277	5.78	50.6	0.0785	1.99
391.3	0.2201	5.59	0.0	0.0394	1.00
340.3	0.1925	4.89			
289.3	0.1823	4.63			
238.3	0.1696	4.31			
187.3	0.1422	3.61			
136.3	0.1280	3.25			
85.3	0.0981	2.49			
34.3	0.0663	1.68			
0.0	0.0394	1.00			

Table 31. Specimen 26 left side crack growth details.

	L1	L2
c2	-2.6390E-06	-4.2117E-06
c1	1.2195E-02	1.3474E-02
c0	1	1
R ²	9.9070E-01	9.8671E-01
Apparent Cycles (K) at 1 mm Length	88.7	480.4

Table 32. Specimen 26 left side crack growth curve fit coefficients.

R1 (137.2K)			R2 (295.7K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
1362.8	0.4779	12.14	1204.3	0.5124	13.02
1311.8	0.4667	11.86	1153.3	0.4833	12.28
1260.8	0.4633	11.77	1102.3	0.4731	12.02
1209.8	0.4445	11.29	1051.3	0.4603	11.69
1158.8	0.4211	10.70	1000.3	0.4586	11.65
1107.8	0.4109	10.44	949.3	0.4433	11.26
1056.8	0.3939	10.00	898.3	0.4305	10.93
1005.8	0.3885	9.87	847.3	0.3966	10.07
954.8	0.3704	9.41	796.3	0.3881	9.86
903.8	0.3534	8.98	745.3	0.3693	9.38
852.8	0.3503	8.90	694.3	0.3463	8.80
801.8	0.3342	8.49	643.3	0.3364	8.55
750.8	0.3220	8.18	592.3	0.3093	7.86
699.8	0.3101	7.88	541.3	0.2951	7.49
648.8	0.2972	7.55	490.3	0.2866	7.28
597.8	0.2798	7.11	439.3	0.2502	6.35
546.8	0.2552	6.48	388.3	0.2451	6.23
495.8	0.2445	6.21	337.3	0.2357	5.99
444.8	0.2386	6.06	286.3	0.1968	5.00
393.8	0.2198	5.58	235.3	0.1865	4.74
342.8	0.2088	5.30	184.3	0.1489	3.78
291.8	0.1969	5.00	133.3	0.1390	3.53
240.8	0.1772	4.50	82.3	0.1036	2.63
189.8	0.1569	3.98	31.3	0.0659	1.67
138.8	0.1474	3.74	0.0	0.0394	1.00
87.8	0.1165	2.96			
36.8	0.0778	1.97			
0.0	0.0394	1.00			

Table 33. Specimen 26 right side crack growth details.

	R1	R2
c2	-3.3125E-06	-4.1248E-06
c1	1.2367E-02	1.4598E-02
c0	1	1
R ²	9.7849E-01	9.9271E-01
Apparent Cycles at 1 mm Length	137.2	295.7

Table 34. Specimen 26 right side crack growth curve fit coefficients.

Specimen	Crack Label	Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
-26 (0.325 OHT x 1500K)	R1	-7.23	271.17
	R2	-7.71	94.67
	L1	7.99	280.22
	L2	8.44	109.01

Table 35. Crack angle details for specimen 26.

Figure 65. Specimen 27 montage with crack labels.

Specimen	Crack Label	Crack Label	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-27 (0.325 OHT x 1500K)	L1	A	72	94	45.5
	L2	B	84	111.4	36.5
	R1	C	324	355.5	31.7
	R2	D	507	529.1	45.2

Table 36. Specimen 27 crack labels and initiation summary.

Figure 66. Specimen 27 left side crack growth since 1 mm vs. cycle count.

Figure 67. Specimen 27 right side crack growth since 1 mm vs. cycle count.

L1 (94K)			L2 (111.4K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
1406.0	0.4683	11.89	1388.6	0.4507	11.45
1316.0	0.4538	11.53	1298.6	0.4211	10.70
1226.0	0.4312	10.95	1208.6	0.4127	10.48
1136.0	0.4114	10.45	1118.6	0.3930	9.98
1046.0	0.3972	10.09	1028.6	0.3743	9.51
956.0	0.3705	9.41	938.6	0.3530	8.97
866.0	0.3545	9.00	848.6	0.3359	8.53
776.0	0.3443	8.75	758.6	0.3124	7.94
686.0	0.3147	7.99	668.6	0.3025	7.68
596.0	0.2915	7.40	578.6	0.2826	7.18
506.0	0.2631	6.68	488.6	0.2292	5.82
458.0	0.2547	6.47	440.6	0.2292	5.82
416.0	0.2387	6.06	398.6	0.2234	5.67
413.0	0.2315	5.88	395.6	0.2220	5.64
326.0	0.1916	4.87	308.6	0.2073	5.27
272.0	0.1818	4.62	254.6	0.1722	4.37
230.0	0.1760	4.47	212.6	0.1595	4.05
146.0	0.1446	3.67	128.6	0.1311	3.33
56.0	0.1047	2.66	38.6	0.0735	1.87
26.0	0.0740	1.88	8.6	0.0564	1.43
8.0	0.0562	1.43	0.0	0.0394	1.00
0.0	0.0394	1.00			

Table 37. Specimen 27 left side crack growth details.

	L1	L2
c2	-4.2506E-06	-4.0864E-06
c1	1.3380E-02	1.2761E-02
c0	1	1
R ²	9.8567E-01	9.8448E-01
Apparent Cycles (K) at 1 mm Length	94.0	111.4

Table 38. Specimen 27 left side crack growth curve fit coefficients.

R1 (355.5K)			R2 (529.1K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
1144.5	0.3686	9.36	970.9	0.3478	8.83
1054.5	0.3485	8.85	880.9	0.3180	8.08
964.5	0.3358	8.53	790.9	0.2995	7.61
874.5	0.3161	8.03	700.9	0.2924	7.43
784.5	0.2992	7.60	610.9	0.2543	6.46
694.5	0.2851	7.24	520.9	0.2428	6.17
604.5	0.2527	6.42	430.9	0.2301	5.85
514.5	0.2400	6.10	340.9	0.1960	4.98
424.5	0.2161	5.49	250.9	0.1609	4.09
334.5	0.1936	4.92	160.9	0.1384	3.51
244.5	0.1613	4.10	70.9	0.1009	2.56
196.5	0.1557	3.96	22.9	0.0506	1.29
154.5	0.1400	3.56	0.0	0.0394	1.00
151.5	0.1386	3.52			
64.5	0.0866	2.20			
10.5	0.0525	1.33			
0.0	0.0394	1.00			

Table 39. Specimen 27 right side crack growth details

	R1	R2
c2	-5.2994E-06	-5.8804E-06
c1	1.2968E-02	1.3329E-02
c0	1	1
R ²	9.7958E-01	9.8368E-01
Apparent Cycles (K) at 1 mm Length	355.5	529.1

Table 40. Specimen 27 right side crack growth curve fit coefficients

C. 40% OHT Reamed Specimens

Figure 68. Specimen 08 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-08 (0.400 OHT x 1000K)	L1	A	30	61.2	32.1
	R1	B	40	63	43.5
	L2	B	40	56.7	59.9
	R2	C	60	74.3	69.9

Table 41. Specimen 08 crack labels and initiation summary.

Figure 69. Specimen 08 left side crack growth since 1 mm vs. cycle count.

Figure 70. Specimen 08 right side crack growth since 1 mm vs. cycle count.

L1 (61.2K)			L2 (56.7K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
938.8	0.5888	14.96	943.3	0.5654	14.36
878.8	0.5740	14.58	883.3	0.5600	14.22
818.8	0.5480	13.92	823.3	0.5231	13.29
758.8	0.5207	13.22	763.3	0.4876	12.38
698.8	0.4824	12.25	703.3	0.4751	12.07
638.8	0.4486	11.40	643.3	0.4518	11.48
578.8	0.4377	11.12	583.3	0.4147	10.53
518.8	0.4035	10.25	523.3	0.3944	10.02
458.8	0.3859	9.80	463.3	0.3740	9.50
398.8	0.3597	9.14	403.3	0.3212	8.16
338.8	0.3258	8.28	343.3	0.3071	7.80
278.8	0.2834	7.20	283.3	0.2795	7.10
218.8	0.2670	6.78	223.3	0.2593	6.59
158.8	0.2182	5.54	163.3	0.2221	5.64
98.8	0.1633	4.15	103.3	0.1550	3.94
80.8	0.1484	3.77	85.3	0.1375	3.49
38.8	0.1099	2.79	43.3	0.1033	2.62
18.8	0.0691	1.75	23.3	0.0744	1.89
8.8	0.0479	1.22	13.3	0.0541	1.37
0.0	0.0394	1.00	3.3	0.0460	1.17
			0.0	0.0394	1.00

Table 42. Specimen 08 left side crack growth details.

	L1	L2
c2	-1.1071E-05	-1.0075E-05
c1	2.4674E-02	2.3219E-02
c0	1	1
R ²	9.8499E-01	9.8750E-01
Apparent Cycles (K) at 1 mm Length	61.2	56.7

Table 43. Specimen 08 left side crack growth curve fit coefficients.

R1 (63K)			R2 (74.3K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
937.0	0.5124	13.02	925.7	0.5397	13.71
877.0	0.5056	12.84	865.7	0.5050	12.83
817.0	0.5037	12.80	805.7	0.4783	12.15
757.0	0.4805	12.20	745.7	0.4676	11.88
697.0	0.4591	11.66	685.7	0.4459	11.32
637.0	0.4120	10.46	625.7	0.4179	10.61
577.0	0.3972	10.09	565.7	0.3802	9.66
517.0	0.3678	9.34	505.7	0.3639	9.24
457.0	0.3331	8.46	445.7	0.3464	8.80
397.0	0.2903	7.37	385.7	0.3127	7.94
337.0	0.2595	6.59	325.7	0.2896	7.36
277.0	0.2408	6.12	265.7	0.2549	6.47
217.0	0.2072	5.26	205.7	0.2338	5.94
157.0	0.1738	4.41	145.7	0.1804	4.58
97.0	0.1510	3.83	85.7	0.1344	3.41
79.0	0.1240	3.15	67.7	0.1153	2.93
37.0	0.0741	1.88	25.7	0.0761	1.93
17.0	0.0487	1.24	5.7	0.0507	1.29
7.0	0.0488	1.24	0.0	0.0394	1.00
0.0	0.0394	1.00			

Table 44. Specimen 08 right side crack growth details.

	R1	R2
c2	-7.8014E-06	-9.7214E-06
c1	2.0365E-02	2.1975E-02
c0	1	1
R ²	9.8925E-01	9.9321E-01
Apparent Cycles (K) at 1 mm Length	63.0	74.3

Table 45. Specimen 08 right side crack growth curve fit coefficients

		Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
Specimen	Crack Label		
-08 (0.400 OHT x 1000K)	R1	-6.34	264.96
	R2	-6.40	96.72
	L1	8.07	270.71
	L2	8.56	83.25

Table 46. Crack angle details for specimen 08.

Figure 71. Specimen 17 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-17 (0.400 OHT x 1000K)	R1	A	46	58.5	80.0
	L1	B	56	79.7	42.2
	R2	C	68	87.2	52.1
	L2	C	68	75.5	133.3
	R3	D	168	186.9	52.9
	L3	E	328	372.2	22.6

Table 47. Specimen 17 crack labels and initiation summary.

Figure 72. Specimen 17 left side crack growth since 1 mm vs. cycle count.

Figure 73. Specimen 17 right side crack growth since 1 mm vs. cycle count.

L1 (79.7K)			L2 (75.5K)			L3 (372.2K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
920.3	0.6267	15.92	924.5	0.6149	15.62	627.8	0.2407	6.11
888.3	0.5810	14.76	892.5	0.5968	15.16	595.8	0.2337	5.94
856.3	0.5753	14.61	860.5	0.5899	14.98	563.8	0.2298	5.84
824.3	0.5703	14.49	828.5	0.5885	14.95	531.8	0.2278	5.79
792.3	0.5424	13.78	796.5	0.5603	14.23	499.8	0.2194	5.57
760.3	0.5410	13.74	764.5	0.5451	13.85	467.8	0.1958	4.97
728.3	0.5313	13.49	732.5	0.5106	12.97	435.8	0.1915	4.86
696.3	0.5242	13.32	700.5	0.5044	12.81	403.8	0.1915	4.86
664.3	0.4990	12.68	668.5	0.4808	12.21	371.8	0.1901	4.83
632.3	0.4865	12.36	636.5	0.4777	12.13	339.8	0.1735	4.41
600.3	0.4436	11.27	604.5	0.4431	11.25	307.8	0.1721	4.37
568.3	0.4295	10.91	572.5	0.4387	11.14	275.8	0.1643	4.17
536.3	0.4225	10.73	540.5	0.4166	10.58	243.8	0.1559	3.96
504.3	0.4045	10.27	508.5	0.4125	10.48	211.8	0.1462	3.71
472.3	0.3844	9.76	476.5	0.4094	10.40	179.8	0.1251	3.18
440.3	0.3579	9.09	444.5	0.3906	9.92	147.8	0.1044	2.65
408.3	0.3508	8.91	412.5	0.3284	8.34	115.8	0.0656	1.67
376.3	0.3453	8.77	380.5	0.3270	8.31	83.8	0.0573	1.46
344.3	0.3335	8.47	348.5	0.3172	8.06	51.8	0.0554	1.41
312.3	0.3003	7.63	316.5	0.2866	7.28	19.8	0.0471	1.20
280.3	0.2672	6.79	284.5	0.2846	7.23	0.0	0.0394	1.00
248.3	0.2474	6.28	252.5	0.2777	7.05			
216.3	0.2430	6.17	220.5	0.2501	6.35			
184.3	0.2165	5.50	188.5	0.2276	5.78			
152.3	0.2134	5.42	156.5	0.2202	5.59			
120.3	0.1920	4.88	124.5	0.2119	5.38			
88.3	0.1679	4.26	92.5	0.1747	4.44			
56.3	0.1401	3.56	60.5	0.1408	3.58			
24.3	0.0999	2.54	28.5	0.1029	2.61			
0.0	0.0394	1.00	0.0	0.0394	1.00			

Table 48. Specimen 17 left side crack growth details.

	L1	L2	L3
c2	-9.1402E-06	-9.0449E-06	-7.2290E-06
c1	2.3711E-02	2.3645E-02	1.2624E-02
c0	1	1	1
R ²	9.7330E-01	9.8020E-01	9.7573E-01
Apparent Cycles (K) at 1 mm Length	79.7	75.5	372.2

Table 49. Specimen 17 left side crack growth curve fit coefficients.

R1 (58.5K)			R2 (87.2K)			R3 (186.9K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
941.5	0.6182	15.70	912.8	0.6215	15.79	813.1	0.2854	7.25
909.5	0.6152	15.63	880.8	0.6215	15.79	781.1	0.2740	6.96
877.5	0.6138	15.59	848.8	0.6201	15.75	749.1	0.2588	6.57
845.5	0.6118	15.54	816.8	0.5838	14.83	717.1	0.2560	6.50
813.5	0.6105	15.51	784.8	0.5768	14.65	685.1	0.2533	6.43
781.5	0.6055	15.38	752.8	0.5616	14.26	653.1	0.2449	6.22
749.5	0.5737	14.57	720.8	0.5471	13.90	621.1	0.2322	5.90
717.5	0.5543	14.08	688.8	0.5388	13.68	589.1	0.2322	5.90
685.5	0.5336	13.55	656.8	0.5206	13.22	557.1	0.2142	5.44
653.5	0.5211	13.24	624.8	0.4999	12.70	525.1	0.2111	5.36
621.5	0.5014	12.74	592.8	0.4860	12.34	493.1	0.2097	5.33
589.5	0.5000	12.70	560.8	0.4694	11.92	461.1	0.2083	5.29
557.5	0.4861	12.35	528.8	0.4510	11.45	429.1	0.2056	5.22
525.5	0.4654	11.82	496.8	0.4191	10.65	397.1	0.2000	5.08
493.5	0.4359	11.07	464.8	0.4150	10.54	365.1	0.1862	4.73
461.5	0.4249	10.79	432.8	0.3788	9.62	333.1	0.1654	4.20
429.5	0.4083	10.37	400.8	0.3788	9.62	301.1	0.1489	3.78
397.5	0.3918	9.95	368.8	0.3591	9.12	269.1	0.1445	3.67
365.5	0.3643	9.25	336.8	0.3258	8.28	237.1	0.1376	3.49
333.5	0.3518	8.94	304.8	0.3134	7.96	205.1	0.1224	3.11
301.5	0.3228	8.20	272.8	0.2884	7.33	173.1	0.1155	2.93
269.5	0.3061	7.78	240.8	0.2746	6.98	141.1	0.1113	2.83
237.5	0.2840	7.21	208.8	0.2495	6.34	109.1	0.0934	2.37
205.5	0.2619	6.65	176.8	0.2424	6.16	77.1	0.0920	2.34
173.5	0.2329	5.92	144.8	0.2078	5.28	45.1	0.0695	1.77
141.5	0.2150	5.46	112.8	0.1780	4.52	13.1	0.0668	1.70
109.5	0.1857	4.72	80.8	0.1503	3.82	0.0	0.0394	1.00
77.5	0.1516	3.85	48.8	0.1161	2.95			
45.5	0.1153	2.93	16.8	0.0815	2.07			
13.5	0.0790	2.01	0.0	0.0394	1.00			
9.5	0.0568	1.44						
0.0	0.0394	1.00						

Table 50. Specimen 17 right side crack growth details

	R1	R2	R3
c2	-1.2907E-05	-1.0789E-05	-5.4390E-06
c1	2.7778E-02	2.5887E-02	1.1657E-02
c0	1	1	1
R ²	9.9218E-01	9.9060E-01	9.8281E-01
Apparent Cycles (K) at 1 mm Length	58.5	87.2	186.9

Table 51. Specimen 17 right side crack growth curve fit coefficients

Specimen	Crack Label	Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
-17 (0.400 OHT x 1000K)	R1	-6.14	274.63
	R2	-7.05	100.96
	R3	-4.49	73.04
	L1	7.89	271.74
	L2	7.24	96.17
	L3	1.07	76.62

Table 52. Crack angle details for specimen 17.

Figure 74. Specimen 18 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-18 (0.400 OHT x 1000K)	R1	A	44	68	41.7
	L2	B	58	79.1	47.4
	R2	B	58	70.2	82.0
	L1	B	58	64.2	161.3
	L3	C	160	184.7	40.5

Table 53. Specimen 18 crack labels and initiation summary.

Figure 75. Specimen 18 left side crack growth since 1 mm vs. cycle count.

Figure 76. Specimen 18 right side crack growth since 1 mm vs. cycle count.

L1 (64.2K)			L2 (79.1K)			L3 (184.7K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
935.8	0.5992	15.22	920.9	0.6288	15.97	815.3	0.2462	6.25
875.8	0.5541	14.07	860.9	0.6257	15.89	755.3	0.2435	6.18
815.8	0.5256	13.35	800.9	0.5946	15.10	695.3	0.2353	5.98
755.8	0.4859	12.34	740.9	0.5699	14.48	635.3	0.2131	5.41
695.8	0.4666	11.85	680.9	0.5385	13.68	575.3	0.2022	5.13
635.8	0.4420	11.23	620.9	0.5219	13.26	515.3	0.1965	4.99
575.8	0.4254	10.80	560.9	0.4983	12.66	455.3	0.1870	4.75
515.8	0.3799	9.65	500.9	0.4367	11.09	395.3	0.1734	4.40
455.8	0.3742	9.51	440.9	0.3941	10.01	335.3	0.1583	4.02
395.8	0.3415	8.67	380.9	0.3681	9.35	275.3	0.1414	3.59
335.8	0.3000	7.62	320.9	0.3244	8.24	215.3	0.1304	3.31
275.8	0.2753	6.99	260.9	0.2874	7.30	155.3	0.0922	2.34
215.8	0.2068	5.25	200.9	0.2434	6.18	95.3	0.0873	2.22
155.8	0.1899	4.82	140.9	0.1915	4.86	35.3	0.0750	1.91
125.8	0.1752	4.45	110.9	0.1601	4.07	5.3	0.0478	1.21
95.8	0.1374	3.49	80.9	0.1560	3.96	0.0	0.0394	1.00
35.8	0.0898	2.28	20.9	0.0954	2.42			
21.8	0.0913	2.32	6.9	0.0566	1.44			
11.8	0.0547	1.39	0.0	0.0394	1.00			
0.0	0.0394	1.00						

Table 54. Specimen 18 left side crack growth details.

	L1	L2	L3
c2	-8.4624E-06	-1.1142E-05	-5.2979E-06
c1	2.2178E-02	2.6532E-02	1.0674E-02
c0	1	1	1
R ²	9.8853E-01	9.9436E-01	9.8602E-01
Apparent Cycles (K) at 1 mm Length	64.2	79.1	184.7

Table 55. Specimen 18 left side crack growth curve fit coefficients.

R1 (68K)			R2 (70.2K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
932.0	0.6229	15.82	929.8	0.6213	15.78
872.0	0.6215	15.79	869.8	0.6199	15.75
812.0	0.6215	15.79	809.8	0.5852	14.86
752.0	0.6159	15.64	749.8	0.5503	13.98
692.0	0.5739	14.58	689.8	0.5199	13.21
632.0	0.5460	13.87	629.8	0.4783	12.15
572.0	0.5101	12.96	569.8	0.4572	11.61
512.0	0.4711	11.97	509.8	0.4318	10.97
452.0	0.4321	10.97	449.8	0.3917	9.95
392.0	0.4014	10.20	389.8	0.3530	8.97
332.0	0.3486	8.85	329.8	0.3349	8.51
272.0	0.3140	7.98	269.8	0.2970	7.54
212.0	0.2693	6.84	209.8	0.2513	6.38
152.0	0.2138	5.43	149.8	0.2026	5.15
122.0	0.2002	5.08	119.8	0.1925	4.89
92.0	0.1698	4.31	89.8	0.1564	3.97
32.0	0.1106	2.81	29.8	0.0902	2.29
18.0	0.0743	1.89	15.8	0.0650	1.65
8.0	0.0548	1.39	5.8	0.0582	1.48
0.0	0.0394	1.00	0.0	0.0394	1.00

Table 56. Specimen 18 right side crack growth details

	R1	R2
c2	-1.4332E-05	-1.0466E-05
c1	2.9495E-02	2.5388E-02
c0	1	1
R ²	9.9427E-01	9.9046E-01
Apparent Cycles (K) at 1 mm Length	68.0	70.2

Table 57. Specimen 18 right side crack growth curve fit coefficients

		Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
Specimen	Crack Label		
-18 (0.400 OHT x 1000K)	R1	-7.55	282.95
	R2	-7.54	100.49
	L1	7.22	273.04
	L2	6.88	106.70
	L3	3.20	82.21

Table 58. Crack angle details for specimen 18.

Figure 77. Specimen 19 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-19	L2	A	34	49.5	64.5
(0.400 OHT	L1	B	44	53.6	104.2
x 1000K)	R1	C	46	61	66.7
	R2	D	54	61.8	128.2

Table 59. Specimen 19 crack labels and initiation summary.

Figure 78. Specimen 19 left side crack growth since 1 mm vs. cycle count.

Figure 79. Specimen 19 right side crack growth since 1 mm vs. cycle count.

L1 (53.6K)			L2 (49.5K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
946.4	0.5599	14.22	950.5	0.6170	15.67
886.4	0.5350	13.59	890.5	0.5965	15.15
826.4	0.4826	12.26	830.5	0.5604	14.23
766.4	0.4757	12.08	770.5	0.5395	13.70
706.4	0.4714	11.97	710.5	0.5296	13.45
646.4	0.4439	11.27	650.5	0.4777	12.13
586.4	0.4339	11.02	590.5	0.4722	11.99
526.4	0.3879	9.85	530.5	0.4166	10.58
466.4	0.3673	9.33	470.5	0.3946	10.02
406.4	0.3464	8.80	410.5	0.3658	9.29
346.4	0.3273	8.31	350.5	0.3340	8.48
286.4	0.2613	6.64	290.5	0.2874	7.30
226.4	0.2312	5.87	230.5	0.2401	6.10
166.4	0.2146	5.45	170.5	0.2113	5.37
106.4	0.1549	3.94	110.5	0.1550	3.94
46.4	0.0977	2.48	50.5	0.1193	3.03
22.4	0.0817	2.08	26.5	0.1119	2.84
10.4	0.0599	1.52	14.5	0.0635	1.61
0.4	0.0404	1.03	4.5	0.0547	1.39
0.0	0.0394	1.00	0.0	0.0394	1.00

Table 60. Specimen 19 left side crack growth details.

	L1	L2
c2	-1.0697E-05	-9.4864E-06
c1	2.3280E-02	2.4071E-02
c0	1	1
R ²	9.9207E-01	9.9005E-01
Apparent Cycles (K) at 1 mm Length	53.6	49.5

Table 61. Specimen 19 left side crack growth curve fit coefficients.

R1 (61K)			R2 (61.8K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
939.0	0.5813	14.77	938.2	0.6280	15.95
879.0	0.5622	14.28	878.2	0.6230	15.83
819.0	0.5522	14.03	818.2	0.5848	14.85
759.0	0.5054	12.84	758.2	0.5792	14.71
699.0	0.4944	12.56	698.2	0.5361	13.62
639.0	0.4670	11.86	638.2	0.5070	12.88
579.0	0.4437	11.27	578.2	0.4865	12.36
519.0	0.4150	10.54	518.2	0.4423	11.24
459.0	0.3888	9.87	458.2	0.4232	10.75
399.0	0.3526	8.96	398.2	0.3806	9.67
339.0	0.3076	7.81	338.2	0.3368	8.55
279.0	0.2788	7.08	278.2	0.3126	7.94
219.0	0.2391	6.07	218.2	0.2810	7.14
159.0	0.2019	5.13	158.2	0.2190	5.56
99.0	0.1513	3.84	98.2	0.1612	4.09
39.0	0.0883	2.24	38.2	0.1082	2.75
15.0	0.0701	1.78	14.2	0.0532	1.35
3.0	0.0467	1.19	2.2	0.0505	1.28
0.0	0.0394	1.00	0.0	0.0394	1.00

Table 62. Specimen 19 right side crack growth details

	R1	R2
c2	-1.0337E-05	-1.1965E-05
c1	2.4045E-02	2.6919E-02
c0	1	1
R ²	9.9587E-01	9.9364E-01
Apparent Cycles (K) at 1 mm Length	61.0	61.8

Table 63. Specimen 19 right side crack growth curve fit coefficients

		Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
Specimen	Crack Label		
-19 (0.400 OHT x 1000K)	R1	-6.36	269.56
	R2	-7.08	95.30
	L1	8.72	272.50
	L2	8.56	89.85

Table 64. Crack angle details for specimen 19.

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Figure 80. Specimen 10 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-10 (0.475 OHT x 750K)	L3	A	6	8.6	384.6
	R3	B	7.5	24.1	60.2
	L2	B	7.5	23.2	63.7
	L1	C	9	100.2	11.0
	R4	C	9	39.1	33.2
	R2	D	37.5	61.3	42.0
	R1	D	37.5	51	74.1

Table 65. Specimen 10 crack labels and initiation summary.

Figure 81. Specimen 10 left side crack growth since 1 mm vs. cycle count.

Figure 82. Specimen 10 right side crack growth since 1 mm vs. cycle count.

L1 (100.2K)			L2 (23.2K)			L3 (8.6K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
649.8	0.3870	9.83	726.8	0.6189	15.72	741.4	0.6963	17.69
621.3	0.3790	9.63	698.3	0.6141	15.60	712.9	0.6963	17.69
592.8	0.3763	9.56	669.8	0.6072	15.42	684.4	0.6949	17.65
564.3	0.3681	9.35	641.3	0.6045	15.36	655.9	0.6930	17.60
535.8	0.3613	9.18	612.8	0.6019	15.29	627.4	0.6930	17.60
507.3	0.3572	9.07	584.3	0.5938	15.08	598.9	0.6900	17.53
478.8	0.3504	8.90	555.8	0.5789	14.71	570.4	0.6887	17.49
450.3	0.3447	8.75	527.3	0.5682	14.43	541.9	0.6874	17.46
421.8	0.3178	8.07	498.8	0.5518	14.02	513.4	0.6674	16.95
393.3	0.3028	7.69	470.3	0.5163	13.11	484.9	0.6417	16.30
364.8	0.3009	7.64	441.8	0.4974	12.63	456.4	0.6215	15.79
336.3	0.2901	7.37	413.3	0.4744	12.05	427.9	0.5970	15.16
307.8	0.2408	6.12	384.8	0.4620	11.73	399.4	0.5601	14.23
279.3	0.2360	5.99	356.3	0.3858	9.80	370.9	0.5237	13.30
250.8	0.2185	5.55	327.8	0.3785	9.61	342.4	0.4870	12.37
222.3	0.2171	5.51	299.3	0.3527	8.96	313.9	0.4601	11.69
193.8	0.2144	5.45	270.8	0.3390	8.61	285.4	0.4313	10.96
165.3	0.2037	5.17	242.3	0.2986	7.59	256.9	0.4110	10.44
136.8	0.1994	5.07	213.8	0.2931	7.44	228.4	0.4110	10.44
108.3	0.1617	4.11	185.3	0.2592	6.58	199.9	0.3701	9.40
79.8	0.1522	3.87	156.8	0.2391	6.07	171.4	0.3372	8.56
51.3	0.1482	3.76	128.3	0.2132	5.42	142.9	0.3153	8.01
22.8	0.1075	2.73	99.8	0.1485	3.77	114.4	0.2883	7.32
4.8	0.0469	1.19	81.8	0.1255	3.19	96.4	0.2037	5.17
0.0	0.0394	1.00	71.3	0.0978	2.48	85.9	0.1727	4.39
			42.8	0.0964	2.45	57.4	0.1592	4.04
			31.8	0.0586	1.49	46.4	0.1302	3.31
			14.3	0.0567	1.44	28.9	0.1001	2.54
			0.0	0.0394	1.00	0.4	0.0515	1.31
						0.0	0.0394	1.00

Table 66. Specimen 10 left side crack growth details.

	L1	L2	L3
c2	-1.8370E-05	-1.6808E-05	-3.2867E-05
c1	2.5148E-02	3.3223E-02	4.7034E-02
c0	1	1	1
R ²	9.5192E-01	9.9308E-01	9.9201E-01
Apparent Cycles (K) at 1 mm Length	100.2	23.2	8.6

Table 67. Specimen 10 left side crack growth curve fit coefficients.

R1 (51K)			R2 (61.3K)			R3 (24.1K)			R4 (39.1K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
699.0	0.6244	15.86	688.7	0.4288	10.89	725.9	0.6463	16.42	710.90	0.4245	10.78
670.5	0.6230	15.82	660.2	0.4206	10.68	697.4	0.6394	16.24	682.40	0.4135	10.50
642.0	0.6162	15.65	631.7	0.4192	10.65	668.9	0.6325	16.06	653.90	0.4092	10.39
613.5	0.5940	15.09	603.2	0.3959	10.06	640.4	0.6325	16.06	625.40	0.4073	10.34
585.0	0.5859	14.88	574.7	0.3837	9.75	611.9	0.6146	15.61	596.90	0.3976	10.10
556.5	0.5612	14.26	546.2	0.3810	9.68	583.4	0.5934	15.07	568.40	0.3868	9.82
528.0	0.5435	13.80	517.7	0.3604	9.15	554.9	0.5716	14.52	539.90	0.3868	9.82
499.5	0.5134	13.04	489.2	0.3440	8.74	526.4	0.5471	13.90	511.40	0.3568	9.06
471.0	0.4984	12.66	460.7	0.3391	8.61	497.9	0.5319	13.51	482.90	0.3555	9.03
442.5	0.4789	12.16	432.2	0.3310	8.41	469.4	0.4991	12.68	454.40	0.3459	8.79
414.0	0.4720	11.99	403.7	0.3227	8.20	440.9	0.4892	12.43	425.90	0.3350	8.51
385.5	0.4485	11.39	375.2	0.2954	7.50	412.4	0.4504	11.44	397.40	0.3320	8.43
357.0	0.4253	10.80	346.7	0.2881	7.32	383.9	0.4216	10.71	368.90	0.3277	8.32
328.5	0.4212	10.70	318.2	0.2758	7.01	355.4	0.3930	9.98	340.40	0.3182	8.08
300.0	0.3831	9.73	289.7	0.2459	6.25	326.9	0.3796	9.64	311.90	0.2978	7.56
271.5	0.3691	9.38	261.2	0.2416	6.14	298.4	0.3179	8.08	283.40	0.2759	7.01
243.0	0.3404	8.65	232.7	0.2266	5.76	269.9	0.3111	7.90	254.90	0.2647	6.72
214.5	0.2927	7.44	204.2	0.1809	4.60	241.4	0.2729	6.93	226.40	0.2443	6.21
186.0	0.2859	7.26	175.7	0.1809	4.60	212.9	0.2702	6.86	197.90	0.2375	6.03
157.5	0.2723	6.92	147.2	0.1714	4.35	184.4	0.2196	5.58	169.40	0.2344	5.95
129.0	0.2341	5.95	118.7	0.1559	3.96	155.9	0.2168	5.51	140.90	0.2031	5.16
100.5	0.2000	5.08	90.2	0.1516	3.85	127.4	0.1923	4.88	112.40	0.1688	4.29
72.0	0.1755	4.46	61.7	0.1254	3.19	98.9	0.1757	4.46	83.90	0.1592	4.04
54.0	0.1428	3.63	43.7	0.1167	2.96	80.9	0.1303	3.31	65.90	0.1170	2.97
43.5	0.1085	2.76	33.2	0.1012	2.57	70.4	0.1220	3.10	55.40	0.1097	2.79
15.0	0.0714	1.81	4.7	0.0669	1.70	41.9	0.1043	2.65	26.90	0.0829	2.10
4.0	0.0511	1.30	0.0	0.0394	1.00	30.9	0.0542	1.38	15.90	0.0674	1.71
0.0	0.0394	1.00				13.4	0.0522	1.33	0.00	0.0394	1.00
						0.0	0.0394	1.00			

Table 68. Specimen 10 right side crack growth details

	R1	R2	R3	R4
c2	-2.1623E-05	-1.2784E-05	-1.0175E-05	-2.0528E-05
c1	3.6073E-02	2.2831E-02	2.9488E-02	2.7540E-02
c0	1	1	1	1
R ²	9.9179E-01	9.7965E-01	9.9500E-01	9.9179E-01
Apparent Cycles (K) at 1 mm Length	51.0	61.3	24.1	39.1

Table 69. Specimen 10 right side crack growth curve fit coefficients

		Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
Specimen	Crack Label		
-10 (0.475 OHT x 750K)	R1	-6.61	253.41
	R2	-4.44	285.46
	R3	-4.73	106.93
	R4	-4.50	69.51
	L1	5.49	261.05
	L2	8.90	289.13
	L3	9.28	89.42

Table 70. Crack angle details for specimen 10.

Figure 83. Specimen 11 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-11 (0.475 OHT x 750K)	L2	A	10.5	35.3	40.3
	L3	B	15	67.2	19.2
	R2	C	39	73.7	28.8
	R1	C	39	55.6	60.2
	R3	C	39	51.7	78.7
	L1	D	255	274.2	52.1

Table 71. Specimen 11 crack labels and initiation summary.

Figure 84. Specimen 11 left side crack growth since 1 mm vs. cycle count.

Figure 85. Specimen 11 right side crack growth since 1 mm vs. cycle count.

L1 (274.2K)			L2 (35.3K)			L3 (67.2K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
475.8	0.3299	8.38	714.7	0.6947	17.64	682.8	0.6950	17.65
460.8	0.2407	6.11	699.7	0.6772	17.20	667.8	0.6672	16.95
436.8	0.2237	5.68	675.7	0.6709	17.04	643.8	0.6564	16.67
412.8	0.2216	5.63	651.7	0.6667	16.93	619.8	0.6332	16.08
388.8	0.2153	5.47	627.7	0.6410	16.28	595.8	0.6332	16.08
364.8	0.2089	5.31	603.7	0.6249	15.87	571.8	0.6285	15.96
340.8	0.2068	5.25	579.7	0.6143	15.60	547.8	0.6221	15.80
316.8	0.1835	4.66	555.7	0.6059	15.39	523.8	0.6113	15.53
292.8	0.1622	4.12	531.7	0.5877	14.93	499.8	0.5952	15.12
268.8	0.1559	3.96	507.7	0.5707	14.49	475.8	0.5783	14.69
244.8	0.1260	3.20	483.7	0.5425	13.78	451.8	0.5516	14.01
220.8	0.1193	3.03	459.7	0.5358	13.61	427.8	0.5456	13.86
196.8	0.1126	2.86	435.7	0.4951	12.58	403.8	0.5426	13.78
172.8	0.1060	2.69	411.7	0.4582	11.64	379.8	0.5088	12.92
148.8	0.1017	2.58	387.7	0.4515	11.47	355.8	0.4980	12.65
124.8	0.0951	2.41	363.7	0.4468	11.35	331.8	0.4748	12.06
100.8	0.0801	2.03	339.7	0.4003	10.17	307.8	0.4480	11.38
76.8	0.0771	1.96	315.7	0.3767	9.57	283.8	0.4193	10.65
52.8	0.0771	1.96	291.7	0.3485	8.85	259.8	0.3885	9.87
28.8	0.0643	1.63	267.7	0.3040	7.72	235.8	0.3568	9.06
4.8	0.0493	1.25	243.7	0.2955	7.51	211.8	0.3462	8.79
0.0	0.0394	1.00	219.7	0.2801	7.11	187.8	0.3139	7.97
			195.7	0.2547	6.47	163.8	0.2923	7.42
			171.7	0.2346	5.96	139.8	0.2732	6.94
			147.7	0.2113	5.37	115.8	0.2409	6.12
			123.7	0.2083	5.29	91.8	0.2172	5.52
			99.7	0.1909	4.85	67.8	0.2088	5.30
			75.7	0.1287	3.27	43.8	0.1841	4.68
			51.7	0.1224	3.11	19.8	0.1256	3.19
			27.7	0.0531	1.35	0.0	0.0394	1.00
			3.7	0.0437	1.11			
			0.0	0.0394	1.00			

Table 72. Specimen 11 left side crack growth details.

	L1	L2	L3
c2	9.1280E-06	-1.0673E-05	-2.9088E-05
c1	8.2839E-03	3.1178E-02	4.2995E-02
c0	1	1	1
R ²	9.4924E-01	9.9520E-01	9.8324E-01
Apparent Cycles (K) at 1 mm Length	274.2	35.3	67.2

Table 73. Specimen 11 left side crack growth curve fit coefficients.

R1 (55.6K)			R2 (73.7K)			R3 (51.7K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
694.4	0.5585	14.18	676.3	0.4750	12.06	698.3	0.7052	17.91
679.4	0.5585	14.18	661.3	0.4686	11.90	683.3	0.7022	17.84
655.4	0.5521	14.02	637.3	0.4623	11.74	659.3	0.6980	17.73
631.4	0.5500	13.97	613.3	0.4222	10.72	635.3	0.6652	16.90
607.4	0.5326	13.53	589.3	0.4179	10.62	611.3	0.6311	16.03
583.4	0.4839	12.29	565.3	0.4112	10.45	587.3	0.5973	15.17
559.4	0.4818	12.24	541.3	0.4028	10.23	563.3	0.4934	12.53
535.4	0.4818	12.24	517.3	0.3901	9.91	539.3	0.4904	12.46
511.4	0.4818	12.24	493.3	0.3711	9.43	515.3	0.4857	12.34
487.4	0.4690	11.91	469.3	0.3562	9.05	491.3	0.4762	12.10
463.4	0.4642	11.79	445.3	0.3474	8.83	467.3	0.4732	12.02
439.4	0.4364	11.09	421.3	0.3217	8.17	443.3	0.4394	11.16
415.4	0.3899	9.90	397.3	0.3110	7.90	419.3	0.4244	10.78
391.4	0.3791	9.63	373.3	0.3080	7.82	395.3	0.4244	10.78
367.4	0.3791	9.63	349.3	0.3038	7.72	371.3	0.4181	10.62
343.4	0.3707	9.42	325.3	0.2826	7.18	347.3	0.3861	9.81
319.4	0.3473	8.82	301.3	0.2739	6.96	323.3	0.3753	9.53
295.4	0.3219	8.18	277.3	0.2692	6.84	299.3	0.3583	9.10
271.4	0.3092	7.85	253.3	0.2481	6.30	275.3	0.3477	8.83
247.4	0.3005	7.63	229.3	0.2289	5.81	251.3	0.3026	7.68
223.4	0.2900	7.36	205.3	0.2247	5.71	227.3	0.2983	7.58
199.4	0.2771	7.04	181.3	0.2180	5.54	203.3	0.2771	7.04
175.4	0.2158	5.48	157.3	0.2053	5.22	179.3	0.2629	6.68
151.4	0.2137	5.43	133.3	0.1863	4.73	155.3	0.2351	5.97
127.4	0.1884	4.78	109.3	0.1631	4.14	131.3	0.2223	5.65
103.4	0.1671	4.24	85.3	0.1229	3.12	107.3	0.2002	5.09
79.4	0.1351	3.43	61.3	0.1013	2.57	83.3	0.1658	4.21
55.4	0.0879	2.23	37.3	0.0894	2.27	59.3	0.1310	3.33
31.4	0.0663	1.69	13.3	0.0699	1.78	35.3	0.1162	2.95
7.4	0.0569	1.45	0.0	0.0394	1.00	11.3	0.0746	1.89
0.0	0.0394	1.00				0.0	0.0394	1.00

Table 74. Specimen 11 right side crack growth details

	R1	R2	R3
c2	-1.5399E-05	-1.1693E-05	-6.9291E-06
c1	2.9592E-02	2.3495E-02	2.8023E-02
c0	1	1	1
R ²	9.9256E-01	9.8221E-01	9.6647E-01
Apparent Cycles (K) at 1 mm Length	55.6	73.7	51.7

Table 75. Specimen 11 right side crack growth curve fit coefficients

Specimen	Crack Label	Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
-11 (0.475 OHT x 750K)	R1	-6.34	253.62
	R2	-4.37	288.36
	R3	-6.69	89.77
	L1	3.89	246.46
	L2	8.48	273.27
	L3	8.90	84.18

Table 76. Crack angle details for specimen 11.

Figure 86. Specimen 12 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-12 (0.475 OHT x 750K)	R3	A	45	53.4	119.0
	R1	B	49.5	52.3	357.1
	L3	C	114	191.7	12.9
	R2	D	121.5	157.1	28.1
	L2	D	121.5	147	39.2
	L1	E	304.5	316.5	83.3

Table 77. Specimen 12 crack labels and initiation summary.

Figure 87. Specimen 12 left side crack growth since 1 mm vs. cycle count.

Figure 88. Specimen 12 right side crack growth since 1 mm vs. cycle count.

L1 (316.5K)			L2 (147K)			L3 (191.7K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
433.5	0.1701	4.32	603.0	0.6151	15.62	558.3	0.6194	15.73
384.0	0.1638	4.16	553.5	0.5641	14.33	508.8	0.6123	15.55
334.5	0.1506	3.83	504.0	0.4742	12.05	459.3	0.5881	14.94
285.0	0.1305	3.32	454.5	0.4201	10.67	409.8	0.5687	14.45
235.5	0.1261	3.20	405.0	0.3787	9.62	360.3	0.5363	13.62
186.0	0.1189	3.02	355.5	0.2825	7.18	310.8	0.4608	11.70
136.5	0.1158	2.94	306.0	0.2028	5.15	261.3	0.4376	11.12
87.0	0.1113	2.83	256.5	0.1578	4.01	211.8	0.4075	10.35
37.5	0.1113	2.83	207.0	0.1507	3.83	162.3	0.3183	8.08
4.5	0.0541	1.37	174.0	0.1314	3.34	129.3	0.2179	5.54
0.0	0.0394	1.00	157.5	0.1243	3.16	112.8	0.2134	5.42
			138.0	0.1243	3.16	93.3	0.1941	4.93
			108.0	0.0667	1.70	63.3	0.1334	3.39
			58.5	0.0604	1.53	13.8	0.0448	1.14
			9.0	0.0533	1.35	0.0	0.0394	1.00
			0.0	0.0394	1.00			

Table 78. Specimen 12 left side crack growth details.

	L1	L2	L3
c2	-1.9249E-05	2.9489E-05	-3.7357E-05
c1	1.5334E-02	7.2020E-03	4.7602E-02
c0	1	1	1
R ²	7.4741E-01	9.9100E-01	9.9169E-01
Apparent Cycles (K) at 1 mm Length	316.5	147.0	191.7

Table 79. Specimen 12 left side crack growth curve fit coefficients.

R1 (52.3K)			R2 (157.1K)			R3 (53.4K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
697.7	0.5530	14.05	592.9	0.2086	5.30	696.6	0.6358	16.15
648.2	0.5274	13.40	543.4	0.1662	4.22	647.1	0.6326	16.07
598.7	0.5049	12.83	493.9	0.1662	4.22	597.6	0.6199	15.75
549.2	0.4730	12.01	444.4	0.1631	4.14	548.1	0.5682	14.43
499.7	0.4444	11.29	394.9	0.1560	3.96	498.6	0.5618	14.27
450.2	0.4188	10.64	345.4	0.1528	3.88	449.1	0.5205	13.22
400.7	0.3581	9.09	295.9	0.1457	3.70	399.6	0.4557	11.57
351.2	0.3422	8.69	246.4	0.1457	3.70	350.1	0.4201	10.67
301.7	0.3136	7.96	196.9	0.1295	3.29	300.6	0.3979	10.11
268.7	0.2935	7.45	163.9	0.1282	3.26	267.6	0.3660	9.30
252.2	0.2776	7.05	147.4	0.1263	3.21	251.1	0.3277	8.32
232.7	0.2585	6.57	127.9	0.1218	3.09	231.6	0.3277	8.32
202.7	0.2266	5.76	97.9	0.1017	2.58	201.6	0.3046	7.74
153.2	0.2139	5.43	48.4	0.0604	1.53	152.1	0.2852	7.24
103.7	0.1626	4.13	0.0	0.0394	1.00	102.6	0.2166	5.50
69.2	0.1340	3.40				68.1	0.1680	4.27
61.7	0.1269	3.22				60.6	0.1487	3.78
54.2	0.1174	2.98				53.1	0.1328	3.37
39.2	0.1142	2.90				38.1	0.1035	2.63
4.7	0.0755	1.92				3.6	0.0652	1.66
0.2	0.0418	1.06				0.0	0.0394	1.00
0.0	0.0394	1.00						

Table 80. Specimen 12 right side crack growth details

	R1	R2	R3
c2	-1.2645E-05	-1.3548E-05	-2.2196E-05
c1	2.7154E-02	1.3841E-02	3.7235E-02
c0	1	1	1
R ²	9.8965E-01	8.7138E-01	9.8885E-01
Apparent Cycles (K) at 1 mm Length	52.3	157.1	53.4

Table 81. Specimen 12 right side crack growth curve fit coefficients

Specimen	Crack Label	Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
-12 (0.475 OHT x 750K)	R1	-6.63	263.39
	R2	-5.44	285.71
	R3	-7.84	106.37
	L1	-2.34	267.19
	L2	7.16	295.55
	L3	10.73	82.28

Table 82. Crack angle details for specimen 12.

Figure 89. Specimen 13 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-13 (0.475 OHT x 750K)	R4	A	31.5	46.9	64.9
	R1	A	31.5	44.1	79.4
	L2	A	31.5	43.2	85.5
	L1	B	42	52.8	92.6
	R3	C	120	127.1	140.8
	R2	D	180	204.2	41.3

Table 83. Specimen 13 crack labels and initiation summary.

Figure 90. Specimen 13 left side crack growth since 1 mm vs. cycle count.

Figure 91. Specimen 13 right side crack growth since 1 mm vs. cycle count.

L1 (52.8K)			L2 (43.2K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
697.2	0.6062	15.40	706.8	0.6746	17.13
647.7	0.6048	15.36	657.3	0.6690	16.99
598.2	0.5935	15.08	607.8	0.6279	15.95
548.7	0.5697	14.47	558.3	0.6106	15.51
499.2	0.5359	13.61	508.8	0.5585	14.19
449.7	0.4917	12.49	459.3	0.5133	13.04
400.2	0.4678	11.88	409.8	0.4552	11.56
350.7	0.4208	10.69	360.3	0.4510	11.46
301.2	0.3698	9.39	310.8	0.3969	10.08
251.7	0.3212	8.16	261.3	0.3744	9.51
202.2	0.2970	7.54	211.8	0.3298	8.38
152.7	0.2265	5.75	162.3	0.3012	7.65
127.2	0.2065	5.24	136.8	0.2235	5.68
103.2	0.1869	4.75	112.8	0.2150	5.46
76.2	0.1468	3.73	85.8	0.1910	4.85
67.2	0.1440	3.66	76.8	0.1696	4.31
53.7	0.1420	3.61	63.3	0.1664	4.23
5.7	0.0526	1.34	15.3	0.0743	1.89
0.0	0.0394	1.00	4.8	0.0556	1.41
			0.0	0.0394	1.00

Table 84. Specimen 13 left side crack growth details.

	L1	L2
c2	-2.0459E-05	-2.0981E-05
c1	3.5295E-02	3.7303E-02
c0	1	1
R ²	9.9632E-01	9.8781E-01
Apparent Cycles (K) at 1 mm Length	52.8	43.2

Table 85. Specimen 13 left side crack growth curve fit coefficients.

R1 (44.1K)			R2 (204.2K)			R3 (127.1K)			R4 (46.9K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
705.9	0.5771	14.66	545.8	0.2374	6.03	622.9	0.3344	8.49	703.10	0.6270	15.93
656.4	0.5412	13.75	496.3	0.2173	5.52	573.4	0.3129	7.95	653.60	0.6009	15.26
606.9	0.5208	13.23	446.8	0.2001	5.08	523.9	0.2958	7.51	604.10	0.5536	14.06
557.4	0.4784	12.15	397.3	0.1969	5.00	474.4	0.2666	6.77	554.60	0.5007	12.72
507.9	0.4656	11.83	347.8	0.1755	4.46	424.9	0.2534	6.44	505.10	0.4685	11.90
458.4	0.4270	10.85	298.3	0.1496	3.80	375.4	0.2463	6.26	455.60	0.4255	10.81
408.9	0.3924	9.97	248.8	0.1251	3.18	325.9	0.2317	5.89	406.10	0.4198	10.66
359.4	0.3724	9.46	199.3	0.1136	2.89	276.4	0.2036	5.17	356.60	0.3640	9.25
309.9	0.3265	8.29	149.8	0.1107	2.81	226.9	0.1807	4.59	307.10	0.3365	8.55
260.4	0.2992	7.60	100.3	0.0979	2.49	177.4	0.1488	3.78	257.60	0.2846	7.23
210.9	0.2807	7.13	50.8	0.0959	2.43	127.9	0.1328	3.37	208.10	0.2417	6.14
161.4	0.2448	6.22	1.3	0.0415	1.06	78.4	0.1127	2.86	158.60	0.2044	5.19
135.9	0.2118	5.38	0.0	0.0394	1.00	52.9	0.0954	2.42	133.10	0.1973	5.01
111.9	0.1861	4.73				28.9	0.0839	2.13	109.10	0.1715	4.36
84.9	0.1618	4.11				1.9	0.0496	1.26	82.10	0.1458	3.70
75.9	0.1586	4.03				0.0	0.0394	1.00	73.10	0.1385	3.52
62.4	0.1428	3.63							59.60	0.1256	3.19
14.4	0.0805	2.05							11.60	0.0573	1.46
3.9	0.0548	1.39							1.10	0.0420	1.07
0.0	0.0394	1.00							0.00	0.0394	1.00

Table 86. Specimen 13 right side crack growth details.

	R1	R2	R3	R4
c2	-1.7229E-05	-4.4684E-06	-1.0766E-05	-9.0125E-06
c1	3.0495E-02	1.1401E-02	1.8167E-02	2.7033E-02
c0	1	1	1	1
R ²	9.8459E-01	9.6059E-01	9.8364E-01	9.9320E-01
Apparent Cycles (K) at 1 mm Length	44.1	204.2	127.1	46.9

Table 87. Specimen 13 right side crack growth curve fit coefficients

Specimen		Crack Label	Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
-13 (0.475 OHT x 750K)	R1	R1	-5.72	261.48
		R2	-3.14	284.96
		R3	-4.46	106.44
		R4	-6.18	79.18
	L1	L1	8.41	270.15
		L2	8.89	86.76

Table 88. Crack angle details for specimen 13.

E. 55% OHT Reamed Specimens

Figure 92. Specimen 07 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-07 (0.550 OHT x 500K)	R3	A	20	36.3	61.3
	L3	A	20	29.4	106.4
	R1	B	27	104.3	12.9
	L2	B	27	35.7	114.9
	L4	C	71	107.3	27.5
	R2	C	71	78.8	128.2
	L1	D	120	128.1	123.5

Table 89. Specimen 07 crack labels and initiation summary.

Figure 93. Specimen 07 left side crack growth since 1 mm vs. cycle count.

Figure 94. Specimen 07 right side crack growth since 1 mm vs. cycle count.

L1 (128.1K)			L2 (35.7K)			L3 (29.4K)			L4 (107.3K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
371.9	0.4029	10.23	464.3	0.4587	11.65	470.6	0.6283	15.96	392.70	0.3217	8.17
338.9	0.3918	9.95	431.3	0.4450	11.30	437.6	0.6228	15.82	359.70	0.3065	7.79
305.9	0.3377	8.58	398.3	0.4419	11.22	404.6	0.5866	14.90	326.70	0.2746	6.97
272.9	0.3198	8.12	365.3	0.4376	11.11	371.6	0.5576	14.16	293.70	0.2636	6.70
239.9	0.2838	7.21	332.3	0.4252	10.80	338.6	0.5346	13.58	260.70	0.2536	6.44
206.9	0.2546	6.47	299.3	0.4224	10.73	305.6	0.4932	12.53	227.70	0.2230	5.66
173.9	0.2199	5.59	266.3	0.4193	10.65	272.6	0.4654	11.82	194.70	0.2130	5.41
140.9	0.2075	5.27	233.3	0.3753	9.53	239.6	0.4267	10.84	161.70	0.1813	4.61
107.9	0.1687	4.29	200.3	0.3478	8.83	206.6	0.3908	9.93	128.70	0.1783	4.53
74.9	0.1286	3.27	167.3	0.3321	8.43	173.6	0.3536	8.98	95.70	0.1617	4.11
41.9	0.1052	2.67	134.3	0.2922	7.42	140.6	0.2985	7.58	62.70	0.1382	3.51
8.9	0.0649	1.65	101.3	0.2508	6.37	107.6	0.2433	6.18	29.70	0.1078	2.74
1.9	0.0485	1.23	94.3	0.2189	5.56	100.6	0.2295	5.83	22.70	0.0981	2.49
0.0	0.0394	1.00	84.3	0.2092	5.31	90.6	0.2086	5.30	12.70	0.0690	1.75
			68.3	0.1926	4.89	74.6	0.1602	4.07	0.00	0.0394	1.00
			44.3	0.1731	4.40	50.6	0.1407	3.57			
			35.3	0.1421	3.61	41.6	0.1282	3.26			
			33.3	0.1390	3.53	39.6	0.1255	3.19			
			10.3	0.0469	1.19	16.6	0.1103	2.80			
			2.3	0.0438	1.11	8.6	0.0937	2.38			
			0.3	0.0407	1.04	6.6	0.0684	1.74			
			0.0	0.0394	1.00	0.0	0.0394	1.00			

Table 90. Specimen 07 left side crack growth details.

	L1	L2	L3	L4
c2	-1.5120E-05	-7.4206E-05	-4.2497E-05	-3.2610E-05
c1	3.0381E-02	5.5746E-02	5.1707E-02	2.9946E-02
c0	1	1	1	1
R ²	9.9342E-01	9.8568E-01	9.9489E-01	9.5041E-01
Apparent Cycles (K) at 1 mm Length	128.1	35.7	29.4	107.3

Table 91. Specimen 07 left side crack growth curve fit coefficients.

R1 (104.3K)			R2 (78.8K)			R3 (36.3K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
395.7	0.2922	7.42	421.2	0.6038	15.34	463.7	0.6253	15.88
362.7	0.2852	7.24	388.2	0.5823	14.79	430.7	0.6099	15.49
329.7	0.2521	6.40	355.2	0.5698	14.47	397.7	0.5765	14.64
296.7	0.2382	6.05	322.2	0.5556	14.11	364.7	0.5210	13.23
263.7	0.2271	5.77	289.2	0.5208	13.23	331.7	0.4947	12.57
230.7	0.2133	5.42	256.2	0.4945	12.56	298.7	0.4830	12.27
197.7	0.1692	4.30	223.2	0.4364	11.09	265.7	0.4375	11.11
164.7	0.1471	3.74	190.2	0.4158	10.56	232.7	0.4070	10.34
131.7	0.1279	3.25	157.2	0.3589	9.12	199.7	0.3748	9.52
98.7	0.1084	2.75	124.2	0.2752	6.99	166.7	0.3357	8.53
65.7	0.1057	2.68	91.2	0.2049	5.21	133.7	0.2993	7.60
32.7	0.0905	2.30	58.2	0.1344	3.41	100.7	0.2609	6.63
25.7	0.0794	2.02	51.2	0.1330	3.38	93.7	0.1974	5.01
15.7	0.0545	1.38	41.2	0.1311	3.33	83.7	0.1946	4.94
0.0	0.0394	1.00	25.2	0.1019	2.59	67.7	0.1835	4.66
			1.2	0.0455	1.16	43.7	0.1595	4.05
			0.0	0.0394	1.00	34.7	0.1357	3.45
						32.7	0.1327	3.37
						9.7	0.0914	2.32
						1.7	0.0563	1.43
						0.0	0.0394	1.00

Table 92. Specimen 07 right side crack growth details

	R1	R2	R3
c2	-9.3072E-06	-5.7061E-05	-4.4303E-05
c1	2.0006E-02	5.8347E-02	5.1613E-02
c0	1	1	1
R ²	9.7961E-01	9.9520E-01	9.8753E-01
Apparent Cycles (K) at 1 mm Length	104.3	78.8	36.3

Table 93. Specimen 07 right side crack growth curve fit coefficients

Specimen	Crack Label	Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
-07 (0.550 OHT x 500K)	R1	-6.73	253.26
	R2	-5.67	280.16
	R3	-8.20	103.78
	L1	4.13	250.31
	L2	7.58	278.35
	L3	6.60	101.40
	L4	4.01	71.43

Table 94. Crack angle details for specimen 07.

Figure 95. Specimen 23 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-23 (0.550 OHT x 500K)	L3	A	40	55.3	65.4
	R3	B	52	76.7	40.5
	L2	B	52	58.6	151.5
	R4	B	52	57.2	192.3
	R1	B	52	57	200.0
	R2	C	60	74	71.4
	L1	D	78	83.1	196.1

Table 95. Specimen 23 crack labels and initiation summary.

Figure 96. Specimen 23 left side crack growth since 1 mm vs. cycle count.

Figure 97. Specimen 23 right side crack growth since 1 mm vs. cycle count.

L1 (83.1K)			L2 (58.6K)			L3 (55.3K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
416.9	0.3775	9.59	441.4	0.5440	13.82	444.7	0.5965	15.15
384.9	0.3633	9.23	409.4	0.5197	13.20	412.7	0.5612	14.26
352.9	0.3546	9.01	377.4	0.4796	12.18	380.7	0.5582	14.18
320.9	0.3259	8.28	345.4	0.4740	12.04	348.7	0.5170	13.13
288.9	0.3014	7.66	313.4	0.4468	11.35	316.7	0.4871	12.37
256.9	0.2971	7.55	281.4	0.4305	10.93	284.7	0.4668	11.86
224.9	0.2644	6.72	249.4	0.3930	9.98	252.7	0.4244	10.78
192.9	0.2220	5.64	217.4	0.3768	9.57	220.7	0.4122	10.47
160.9	0.2153	5.47	185.4	0.3250	8.26	188.7	0.3614	9.18
128.9	0.1919	4.87	153.4	0.2639	6.70	156.7	0.3262	8.29
96.9	0.1590	4.04	121.4	0.2304	5.85	124.7	0.2765	7.02
64.9	0.1454	3.69	89.4	0.2221	5.64	92.7	0.2327	5.91
32.9	0.0991	2.52	57.4	0.1794	4.56	60.7	0.2040	5.18
0.9	0.0461	1.17	25.4	0.1397	3.55	28.7	0.1577	4.01
0.0	0.0394	1.00	19.4	0.0794	2.02	22.7	0.1252	3.18
			1.4	0.0475	1.21	4.7	0.0612	1.55
			0.0	0.0394	1.00	0.0	0.0394	1.00

Table 96. Specimen 23 left side crack growth details.

	L1	L2	L3
c2	-2.9144E-05	-4.5233E-05	-5.3696E-05
c1	3.2475E-02	4.7962E-02	5.4429E-02
c0	1	1	1
R ²	9.8872E-01	9.8508E-01	9.8334E-01
Apparent Cycles (K) at 1 mm Length	83.1	58.6	55.3

Table 97. Specimen 23 left side crack growth curve fit coefficients.

R1 (57K)			R2 (74K)			R3 (76.7K)			R4 (57.2K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
443.0	0.5687	14.44	426.0	0.3927	9.98	423.3	0.3177	8.07	442.80	0.6170	15.67
411.0	0.5225	13.27	394.0	0.3791	9.63	391.3	0.3110	7.90	410.80	0.5758	14.63
379.0	0.5062	12.86	362.0	0.3601	9.15	359.3	0.2662	6.76	378.80	0.5580	14.17
347.0	0.4911	12.47	330.0	0.3384	8.60	327.3	0.2322	5.90	346.80	0.5253	13.34
315.0	0.4545	11.55	298.0	0.3125	7.94	295.3	0.2295	5.83	314.80	0.5046	12.82
283.0	0.4044	10.27	266.0	0.3031	7.70	263.3	0.2253	5.72	282.80	0.4585	11.65
251.0	0.4031	10.24	234.0	0.2853	7.25	231.3	0.2059	5.23	250.80	0.4434	11.26
219.0	0.3730	9.47	202.0	0.2605	6.62	199.3	0.1827	4.64	218.80	0.3999	10.16
187.0	0.3228	8.20	170.0	0.2291	5.82	167.3	0.1731	4.40	186.80	0.3653	9.28
155.0	0.2971	7.55	138.0	0.2084	5.29	135.3	0.1528	3.88	154.80	0.3260	8.28
123.0	0.2760	7.01	106.0	0.2041	5.19	103.3	0.1238	3.15	122.80	0.2784	7.07
91.0	0.2366	6.01	74.0	0.1633	4.15	71.3	0.0951	2.42	90.80	0.2389	6.07
59.0	0.1919	4.87	42.0	0.1248	3.17	39.3	0.0773	1.96	58.80	0.2062	5.24
27.0	0.1390	3.53	10.0	0.0847	2.15	7.3	0.0622	1.58	26.80	0.1709	4.34
21.0	0.0995	2.53	4.0	0.0508	1.29	1.3	0.0417	1.06	20.80	0.0859	2.18
3.0	0.0626	1.59	0.0	0.0394	1.00	0.0	0.0394	1.00	2.80	0.0601	1.53
0.0	0.0394	1.00							0.00	0.0394	1.00

Table 98. Specimen 23 right side crack growth details

	R1	R2	R3	R4
c2	-4.7458E-05	-3.7374E-05	-1.0353E-05	-5.1925E-05
c1	4.9574E-02	3.6103E-02	2.0485E-02	5.4563E-02
c0	1	1	1	1
R ²	9.7842E-01	9.7739E-01	9.8341E-01	9.8142E-01
Apparent Cycles (K) at 1 mm Length	57.0	74.0	76.7	57.2

Table 99. Specimen 23 right side crack growth curve fit coefficients

		Crack Initiation Point	
Specimen	Crack Label	Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
-23 (0.550 OHT x 500K)	R1	-5.22	253.53
	R2	-5.37	290.35
	R3	-3.00	107.95
	R4	-7.45	80.73
	L1	6.45	254.86
	L2	8.78	289.05
	L3	8.26	92.23

Table 100. Crack angle details for specimen 23.

F. 32.5% OHT Jig Grind Specimens

Figure 98. Specimen 37 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-37	L2	A	51	64.9	71.9
(0.325 OHT	R3	B	99	161	16.1
x 1500K)	R1	C	180	254.3	13.5
Jig Grind	L1	C	180	203	43.5
	R2	D	510	601.8	10.9

Table 101. Specimen 37 crack labels and initiation summary.

Figure 99. Specimen 37 left side crack growth since 1 mm vs. cycle count.

Figure 100. Specimen 37 right side crack growth since 1 mm vs. cycle count.

L1 (203K)			L2 (64.9K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
1297.0	0.4567	11.60	1435.1	0.5033	12.78
1207.0	0.4279	10.87	1345.1	0.4763	12.10
1117.0	0.4117	10.46	1255.1	0.4506	11.44
1027.0	0.3980	10.11	1165.1	0.4300	10.92
937.0	0.3710	9.42	1075.1	0.4069	10.34
847.0	0.3530	8.97	985.1	0.3919	9.95
757.0	0.3210	8.15	895.1	0.3702	9.40
667.0	0.3048	7.74	805.1	0.3403	8.64
577.0	0.2826	7.18	715.1	0.3214	8.16
487.0	0.2578	6.55	625.1	0.2953	7.50
397.0	0.2443	6.20	535.1	0.2740	6.96
307.0	0.2174	5.52	445.1	0.2494	6.34
217.0	0.1802	4.58	355.1	0.2167	5.50
127.0	0.1436	3.65	265.1	0.1992	5.06
31.0	0.0925	2.35	169.1	0.1672	4.25
0.0	0.0394	1.00	115.1	0.1453	3.69
			79.1	0.1315	3.34
			52.1	0.1064	2.70
			34.1	0.0868	2.20
			19.1	0.0770	1.96
			0.0	0.0394	1.00

Table 102. Specimen 37 left side crack growth details.

	L1	L2
c2	-4.6574E-06	-3.8774E-06
c1	1.3743E-02	1.3257E-02
c0	1	1
R ²	9.7000E-01	9.6626E-01
Apparent Cycles (K) at 1 mm Length	203.0	64.9

Table 103. Specimen 37 left side crack growth curve fit coefficients.

R1 (254.3K)			R2 (601.8K)			R3 (161K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
1245.7	0.4729	12.01	898.2	0.2244	5.70	1339.0	0.4648	11.81
1155.7	0.4687	11.90	808.2	0.2225	5.65	1249.0	0.4315	10.96
1065.7	0.4394	11.16	718.2	0.1971	5.01	1159.0	0.4023	10.22
975.7	0.4185	10.63	628.2	0.1927	4.90	1069.0	0.3979	10.11
885.7	0.4057	10.30	538.2	0.1760	4.47	979.0	0.3895	9.89
795.7	0.3834	9.74	448.2	0.1550	3.94	889.0	0.3728	9.47
705.7	0.3569	9.07	358.2	0.1536	3.90	799.0	0.3506	8.90
615.7	0.3361	8.54	268.2	0.1408	3.58	709.0	0.3186	8.09
525.7	0.3162	8.03	178.2	0.1255	3.19	619.0	0.3061	7.77
435.7	0.2870	7.29	88.2	0.1115	2.83	529.0	0.2797	7.10
345.7	0.1760	4.47	0.0	0.0394	1.00	439.0	0.1782	4.53
255.7	0.1675	4.26				349.0	0.1629	4.14
165.7	0.1180	3.00				259.0	0.1267	3.22
75.7	0.0752	1.91				169.0	0.0919	2.33
0.0	0.0394	1.00				73.0	0.0807	2.05
						19.0	0.0416	1.06
						0.0	0.0394	1.00

Table 104. Specimen 37 right side crack growth details

	R1	R2	R3
c2	-4.8002E-06	-5.6809E-06	-2.7677E-06
c1	1.4817E-02	1.0063E-02	1.1623E-02
c0	1	1	1
R ²	9.9548E-01	9.7687E-01	9.9084E-01
Apparent Cycles (K) at 1 mm Length	254.3	601.8	161.0

Table 105. Specimen 37 right side crack growth curve fit coefficients.

		Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
Specimen	Crack Label		
-37 (0.325 OHT x 1500K) Jig Grind	R1	-6.34	284.94
	R2	-0.36	97.41
	R3	-4.65	72.14
	L1	11.94	261.56
	L2	10.68	90.90

Table 106. Crack angle details for specimen 37.

Figure 101. Specimen 39 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-39	L1	A	48	86.7	25.8
(0.325 OHT	L2	A	48	78.1	33.2
x 1500K)	R1	B	117	134.4	57.5
Jig Grind	R2	C	234	278.7	22.4

Table 107. Specimen 39 crack labels and initiation summary.

Figure 102. Specimen 39 left side crack growth since 1 mm vs. cycle count.

Figure 103. Specimen 39 right side crack growth since 1 mm vs. cycle count.

L1 (86.7K)			L2 (78.1K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
1413.3	0.5100	12.95	1421.9	0.4758	12.09
1323.3	0.4901	12.45	1331.9	0.4714	11.97
1233.3	0.4647	11.80	1241.9	0.4530	11.51
1143.3	0.4449	11.30	1151.9	0.4291	10.90
1053.3	0.4278	10.87	1061.9	0.3867	9.82
963.3	0.4109	10.44	971.9	0.3754	9.53
873.3	0.3812	9.68	881.9	0.3626	9.21
783.3	0.3502	8.89	791.9	0.3189	8.10
693.3	0.3276	8.32	701.9	0.3004	7.63
603.3	0.2963	7.53	611.9	0.2821	7.16
513.3	0.2794	7.10	521.9	0.2718	6.90
423.3	0.2495	6.34	431.9	0.2253	5.72
333.3	0.2069	5.26	341.9	0.1956	4.97
243.3	0.1942	4.93	251.9	0.1715	4.36
147.3	0.1349	3.43	155.9	0.1249	3.17
57.3	0.1177	2.99	65.9	0.1022	2.60
30.3	0.0675	1.71	38.9	0.0810	2.06
12.3	0.0504	1.28	20.9	0.0605	1.54
0.0	0.0394	1.00	5.9	0.0462	1.17
			0.0	0.0394	1.00

Table 108. Specimen 39 left side crack growth details.

	L1	L2
c2	-3.7930E-06	-2.9975E-06
c1	1.3528E-02	1.1994E-02
c0	1	1
R ²	9.8785E-01	9.9011E-01
Apparent Cycles (K) at 1 mm Length	86.7	78.1

Table 109. Specimen 39 left side crack growth curve fit coefficients.

R1 (134.4K)			R2 (278.7K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
1365.6	0.4659	11.83	1221.3	0.4356	11.06
1275.6	0.4460	11.33	1131.3	0.4146	10.53
1185.6	0.4208	10.69	1041.3	0.3824	9.71
1095.6	0.4013	10.19	951.3	0.3586	9.11
1005.6	0.3801	9.65	861.3	0.3428	8.71
915.6	0.3501	8.89	771.3	0.3162	8.03
825.6	0.3275	8.32	681.3	0.2911	7.39
735.6	0.3092	7.85	591.3	0.2557	6.49
645.6	0.2923	7.42	501.3	0.2537	6.44
555.6	0.2742	6.96	411.3	0.2098	5.33
465.6	0.2486	6.31	321.3	0.1917	4.87
375.6	0.2260	5.74	231.3	0.1735	4.41
285.6	0.1892	4.81	141.3	0.1421	3.61
195.6	0.1619	4.11	51.3	0.0846	2.15
99.6	0.1248	3.17	0.0	0.0394	1.00
9.6	0.0611	1.55			
0.0	0.0394	1.00			

Table 110. Specimen 39 right side crack growth details

	R1	R2
c2	-3.6427E-06	-3.6330E-06
c1	1.2534E-02	1.2138E-02
c0	1	1
R ²	9.7971E-01	9.7886E-01
Apparent Cycles (K) at 1 mm Length	134.4	278.7

Table 111. Specimen 39 right side crack growth curve fit coefficients.

		Crack Initiation Point Angle (deg)
Specimen	Crack Label	Angle (deg)
-39 (0.325 OHT x 1500K) Jig Grind	R1	-6.67
	R2	-4.55
	L1	10.00
	L2	9.76

Table 112. Crack angle details for specimen 39.

G. 47.5% OHT Jig Grind Specimens

Figure 104. Specimen 29 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-29 (0.475 OHT x 750K) Jig Grind	R1	A	36	60.5	40.8
	R4	A	36	41.5	181.8
	L3	B	42	59.4	57.5
	L2	C	58.5	74.5	62.5
	L4	D	105	134.8	33.6
	R3	E	120	149.7	33.7
	L1	E	120	134.4	69.4
	R2	E	120	128.7	114.9

Table 113. Specimen 29 crack labels and initiation summary.

Figure 105. Specimen 29 left side crack growth since 1 mm vs. cycle count.

Figure 106. Specimen 29 right side crack growth since 1 mm vs. cycle count.

L1 (134.4K)			L2 (74.5K)			L3 (59.4K)			L4 (134.8K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
615.6	0.3729	9.47	675.5	0.5878	14.93	690.6	0.6262	15.91	615.20	0.3019	7.67
558.6	0.3506	8.90	618.5	0.5516	14.01	633.6	0.6198	15.74	558.20	0.2972	7.55
501.6	0.3474	8.83	561.5	0.5084	12.91	576.6	0.5563	14.13	501.20	0.2862	7.27
444.6	0.3269	8.30	504.5	0.5027	12.77	519.6	0.4584	11.64	444.20	0.2638	6.70
387.6	0.2780	7.06	447.5	0.4556	11.57	462.6	0.4302	10.93	387.20	0.2178	5.53
330.6	0.2667	6.77	390.5	0.4148	10.54	405.6	0.4143	10.52	330.20	0.2052	5.21
273.6	0.2352	5.97	333.5	0.3646	9.26	348.6	0.3670	9.32	273.20	0.1961	4.98
216.6	0.1987	5.05	276.5	0.3316	8.42	291.6	0.3181	8.08	216.20	0.1788	4.54
159.6	0.1809	4.60	219.5	0.2697	6.85	234.6	0.2772	7.04	159.20	0.1315	3.34
102.6	0.1431	3.64	162.5	0.1960	4.98	177.6	0.2631	6.68	102.20	0.0868	2.20
45.6	0.1336	3.39	105.5	0.1694	4.30	120.6	0.1795	4.56	45.20	0.0586	1.49
24.6	0.1104	2.80	84.5	0.1534	3.90	99.6	0.1512	3.84	24.20	0.0492	1.25
5.1	0.0555	1.41	65.0	0.1470	3.73	80.1	0.1407	3.57	4.70	0.0492	1.25
0.0	0.0394	1.00	56.0	0.1425	3.62	71.1	0.1385	3.52	0.00	0.0394	1.00
			45.5	0.1403	3.56	60.6	0.1131	2.87			
			30.5	0.1027	2.61	45.6	0.1051	2.67			
			9.5	0.0716	1.82	24.6	0.0842	2.14			
			2.0	0.0419	1.06	17.1	0.0619	1.57			
			0.0	0.0394	1.00	2.1	0.0596	1.52			
						0.0	0.0394	1.00			

Table 114. Specimen 29 left side crack growth details.

	L1	L2	L3	L4
c2	-1.6265E-05	-1.6517E-05	-9.0862E-06	-7.9843E-06
c1	2.3412E-02	3.1242E-02	2.7585E-02	1.6018E-02
c0	1	1	1	1
R ²	9.5877E-01	9.8802E-01	9.8713E-01	9.8961E-01
Apparent Cycles (K) at 1 mm Length	134.4	74.5	59.4	134.8

Table 115. Specimen 29 left side crack growth curve fit coefficients.

R1 (60.5K)			R2 (128.7K)			R3 (149.7K)			R4 (41.5K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
689.5	0.6039	15.34	621.3	0.2178	5.53	600.3	0.2956	7.51	708.50	0.6384	16.21
632.5	0.5945	15.10	564.3	0.2083	5.29	543.3	0.2798	7.11	651.50	0.6257	15.89
575.5	0.5642	14.33	507.3	0.1720	4.37	486.3	0.2326	5.91	594.50	0.5973	15.17
518.5	0.5044	12.81	450.3	0.1689	4.29	429.3	0.2304	5.85	537.50	0.5293	13.44
461.5	0.4774	12.13	393.3	0.1624	4.12	372.3	0.2178	5.53	480.50	0.4789	12.16
404.5	0.4365	11.09	336.3	0.1592	4.04	315.3	0.1894	4.81	423.50	0.4521	11.48
347.5	0.3861	9.81	279.3	0.1341	3.41	258.3	0.1544	3.92	366.50	0.4190	10.64
290.5	0.3577	9.09	222.3	0.1183	3.01	201.3	0.1495	3.80	309.50	0.3936	10.00
233.5	0.3072	7.80	165.3	0.1069	2.71	144.3	0.1207	3.07	252.50	0.3212	8.16
176.5	0.2410	6.12	108.3	0.0769	1.95	87.3	0.0986	2.51	195.50	0.2658	6.75
119.5	0.2265	5.75	51.3	0.0658	1.67	30.3	0.0687	1.74	138.50	0.2138	5.43
98.5	0.1934	4.91	30.3	0.0547	1.39	9.3	0.0529	1.34	117.50	0.2122	5.39
79.0	0.1665	4.23	10.8	0.0497	1.26	0.0	0.0394	1.00	98.00	0.1854	4.71
70.0	0.1649	4.19	1.8	0.0475	1.21				89.00	0.1618	4.11
59.5	0.1269	3.22	0.0	0.0394	1.00				78.50	0.1491	3.79
44.5	0.0983	2.50							63.50	0.1270	3.23
23.5	0.0841	2.14							42.50	0.1018	2.59
16.0	0.0794	2.02							35.00	0.0908	2.31
1.0	0.0469	1.19							20.00	0.0703	1.79
0.0	0.0394	1.00							17.00	0.0604	1.53
									0.50	0.0428	1.09
									0.00	0.0394	1.00

Table 116. Specimen 29 right side crack growth details

	R1	R2	R3	R4
c2	-1.9155E-05	-4.8561E-06	-5.8385E-06	-1.6521E-05
c1	3.3733E-02	9.9954E-03	1.4020E-02	3.2958E-02
c0	1	1	1	1
R ²	9.8966E-01	9.8419E-01	9.8546E-01	9.9431E-01
Apparent Cycles (K) at 1 mm Length	60.5	128.7	149.7	41.5

Table 117. Specimen 29 right side crack growth curve fit coefficients

Specimen		Crack Label	Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
-29 (0.475 OHT x 750K) Jig Grind	R1	R1	-4.66	257.45
		R2	-0.43	277.21
		R3	-2.17	104.20
		R4	-4.42	75.46
	L1	L1	7.03	254.31
		L2	8.83	289.45
		L3	9.61	105.39
		L4	7.20	77.45

Table 118. Crack angle details for specimen 29.

Figure 107. Specimen 35 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-35	L3	A	22.5	42.8	49.3
(0.475 OHT	R2	B	30	43.1	76.3
x 750K)	R1	C	34.5	48.6	70.9
Jig Grind	L1	D	42	73.1	32.2
	L2	E	64.5	82.1	56.8

Table 119. Specimen 35 crack labels and initiation summary.

Figure 108. Specimen 35 left side crack growth since 1 mm vs. cycle count.

Figure 109. Specimen 35 right side crack growth since 1 mm vs. cycle count.

L1 (73.1K)			L2 (82.1K)			L3 (42.8K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
676.9	0.6295	15.99	667.9	0.3113	7.91	707.2	0.6099	15.49
619.9	0.5734	14.56	610.9	0.3031	7.70	650.2	0.5738	14.58
562.9	0.5435	13.80	553.9	0.2838	7.21	593.2	0.5391	13.69
505.9	0.5042	12.81	496.9	0.2741	6.96	536.2	0.5128	13.02
448.9	0.4713	11.97	439.9	0.2698	6.85	479.2	0.4780	12.14
391.9	0.4362	11.08	382.9	0.2465	6.26	422.2	0.4449	11.30
334.9	0.3935	9.99	325.9	0.2245	5.70	365.2	0.3991	10.14
277.9	0.3508	8.91	268.9	0.2149	5.46	308.2	0.3700	9.40
220.9	0.3000	7.62	211.9	0.1888	4.80	251.2	0.3288	8.35
163.9	0.2407	6.11	154.9	0.1532	3.89	194.2	0.2672	6.79
106.9	0.1573	4.00	97.9	0.1021	2.59	137.2	0.2145	5.45
49.9	0.1195	3.04	40.9	0.0622	1.58	80.2	0.1703	4.33
31.9	0.0770	1.96	22.9	0.0522	1.33	62.2	0.1426	3.62
10.9	0.0449	1.14	1.9	0.0436	1.11	41.2	0.1126	2.86
0.0	0.0394	1.00	0.0	0.0394	1.00	21.7	0.0934	2.37
						12.2	0.0614	1.56
						0.0	0.0394	1.00

Table 120. Specimen 35 left side crack growth details.

	L1	L2	L3
c2	-1.5869E-05	-1.4102E-05	-1.8692E-05
c1	3.2066E-02	1.9453E-02	3.2925E-02
c0	1	1	1
R ²	9.9690E-01	9.9484E-01	9.9273E-01
Apparent Cycles (K) at 1 mm Length	73.1	82.1	42.8

Table 121. Specimen 35 left side crack growth curve fit coefficients.

R1 (48.6K)			R2 (43.1K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
701.4	0.6081	15.44	706.9	0.6108	15.51
644.4	0.5423	13.77	649.9	0.6038	15.34
587.4	0.5277	13.40	592.9	0.5556	14.11
530.4	0.4826	12.26	535.9	0.5289	13.43
473.4	0.4741	12.04	478.9	0.4842	12.30
416.4	0.4392	11.16	421.9	0.4614	11.72
359.4	0.3986	10.12	364.9	0.4153	10.55
302.4	0.3552	9.02	307.9	0.3618	9.19
245.4	0.2962	7.52	250.9	0.3321	8.44
188.4	0.2624	6.67	193.9	0.2719	6.91
131.4	0.2089	5.31	136.9	0.2269	5.76
74.4	0.1607	4.08	79.9	0.1632	4.15
56.4	0.1209	3.07	61.9	0.1295	3.29
35.4	0.1081	2.74	40.9	0.1135	2.88
15.9	0.0717	1.82	21.4	0.0645	1.64
6.4	0.0503	1.28	11.9	0.0573	1.46
0.0	0.0394	1.00	0.0	0.0394	1.00

Table 122. Specimen 35 right side crack growth details

	R1	R2
c2	-1.7883E-05	-1.8482E-05
c1	3.1929E-02	3.3399E-02
c0	1	1
R ²	9.9228E-01	9.9585E-01
Apparent Cycles (K) at 1 mm Length	48.6	43.1

Table 123. Specimen 35 right side crack growth curve fit coefficients

		Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
Specimen	Crack Label		
-35 (0.475 OHT x 750K) Jig Grind	R1	-6.08	277.09
	R2	-6.05	95.65
	L1	7.52	264.48
	L2	8.46	287.58
	L3	9.46	92.55

Table 124. Crack angle details for specimen 35.

Figure 110. Specimen 36 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-36 (0.475 OHT x 750K) Jig Grind	L3	A	22.1	36.7	68.5
	R3	A	22.5	37	69.0
	R1	B	28.5	39.8	88.5
	L2	C	33	58.1	39.8
	L1	D	79.5	86.3	147.1
	R2	E	84	94.6	94.3

Table 125. Specimen 36 crack labels and initiation summary.

Figure 111. Specimen 36 left side crack growth since 1 mm vs. cycle count.

Figure 112. Specimen 36 right side crack growth since 1 mm vs. cycle count.

L1 (86.3K)			L2 (58.1K)			L3 (36.7K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
663.7	0.3329	8.46	691.9	0.6110	15.52	713.3	0.6235	15.84
606.7	0.3189	8.10	634.9	0.5727	14.55	656.3	0.6208	15.77
549.7	0.3063	7.78	577.9	0.5287	13.43	599.3	0.5906	15.00
492.7	0.2881	7.32	520.9	0.4986	12.66	542.3	0.5618	14.27
435.7	0.2700	6.86	463.9	0.4769	12.11	485.3	0.5222	13.26
378.7	0.2500	6.35	406.9	0.4493	11.41	428.3	0.4879	12.39
321.7	0.2358	5.99	349.9	0.4072	10.34	371.3	0.4579	11.63
264.7	0.2145	5.45	292.9	0.3668	9.32	314.3	0.4142	10.52
207.7	0.1863	4.73	235.9	0.3302	8.39	257.3	0.3552	9.02
150.7	0.1647	4.18	178.9	0.2799	7.11	200.3	0.3020	7.67
93.7	0.1115	2.83	121.9	0.2307	5.86	143.3	0.2398	6.09
36.7	0.0989	2.51	64.9	0.1599	4.06	86.3	0.1835	4.66
18.7	0.0878	2.23	46.9	0.1288	3.27	68.3	0.1630	4.14
0.0	0.0394	1.00	25.9	0.0960	2.44	47.3	0.1467	3.73
			21.4	0.0827	2.10	42.8	0.1329	3.38
			0.0	0.0394	1.00	18.8	0.0771	1.96
						5.3	0.0565	1.43
						0.0	0.0394	1.00

Table 126. Specimen 36 left side crack growth details.

	L1	L2	L3
c2	-1.4374E-05	-2.2584E-05	-2.4481E-05
c1	2.0338E-02	3.5402E-02	3.8035E-02
c0	1	1	1
R ²	9.7518E-01	9.8702E-01	9.9357E-01
Apparent Cycles (K) at 1 mm Length	86.3	58.1	36.7

Table 127. Specimen 36 left side crack growth curve fit coefficients.

R1 (39.8K)			R2 (94.6K)			R3 (37K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
710.2	0.5985	15.20	655.4	0.3567	9.06	713.0	0.6170	15.67
653.2	0.5985	15.20	598.4	0.3400	8.63	656.0	0.6139	15.59
596.2	0.5616	14.26	541.4	0.3107	7.89	599.0	0.5593	14.21
539.2	0.5448	13.84	484.4	0.3065	7.78	542.0	0.5328	13.53
482.2	0.5182	13.16	427.4	0.2813	7.14	485.0	0.4922	12.50
425.2	0.4778	12.14	370.4	0.2548	6.47	428.0	0.4656	11.83
368.2	0.4384	11.13	313.4	0.2463	6.26	371.0	0.3972	10.09
311.2	0.3877	9.85	256.4	0.2266	5.76	314.0	0.3638	9.24
254.2	0.3250	8.26	199.4	0.1889	4.80	257.0	0.3317	8.43
197.2	0.2773	7.04	142.4	0.1692	4.30	200.0	0.2648	6.72
140.2	0.2370	6.02	85.4	0.1187	3.02	143.0	0.2215	5.63
83.2	0.1766	4.49	28.4	0.0867	2.20	86.0	0.1559	3.96
65.2	0.1520	3.86	10.4	0.0783	1.99	68.0	0.1392	3.54
44.2	0.1296	3.29	0.0	0.0394	1.00	47.0	0.1110	2.82
39.7	0.1282	3.26				42.5	0.1026	2.61
15.7	0.0689	1.75				18.5	0.0655	1.66
2.2	0.0494	1.25				5.0	0.0624	1.58
0.0	0.0394	1.00				0.0	0.0394	1.00

Table 128. Specimen 36 right side crack growth details

	R1	R2	R3
c2	-2.2994E-05	-1.4892E-05	-1.5906E-05
c1	3.6274E-02	2.1457E-02	3.1921E-02
c0	1	1	1
R ²	9.9392E-01	9.7761E-01	9.9639E-01
Apparent Cycles (K) at 1 mm Length	39.8	94.6	37.0

Table 129. Specimen 36 right side crack growth curve fit coefficients.

		Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
Specimen	Crack Label		
-36 (0.475 OHT x 750K) Jig Grind	R1	-6.99	270.62
	R2	-2.47	100.95
	R3	-5.46	74.64
	L1	5.54	262.14
	L2	8.71	286.28
	L3	9.52	93.76

Table 130. Crack angle details for specimen 36.

H. 47.5% OHT Shot Peened Specimens

Figure 113. Specimen 30 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-30 (0.475 OHT x 750K) Shot Peen	L2	A	30	130	10.0
	R2	A	30	94.7	15.5
	R3	A	30	75.2	22.1
	R1	B	174	472.7	3.3
	L1	C	390	463.8	13.6

Table 131. Specimen 30 crack labels and initiation summary.

Figure 114. Specimen 30 left side crack growth since 1 mm vs. cycle count.

Figure 115. Specimen 30 right side crack growth since 1 mm vs. cycle count.

L1 (463.8K)			L2 (130K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
286.2	0.1120	2.84	620.0	0.2761	7.01
214.2	0.0873	2.22	548.0	0.2510	6.37
142.2	0.0835	2.12	476.0	0.1975	5.02
70.2	0.0778	1.98	404.0	0.1856	4.72
0.0	0.0394	1.00	332.0	0.1819	4.62
			260.0	0.1737	4.41
			188.0	0.1522	3.87
			116.0	0.0817	2.07
			44.0	0.0607	1.54
			0.0	0.0394	1.00

Table 132. Specimen 30 left side crack growth details.

	L1	L2
c2	-1.5064E-05	-5.8680E-06
c1	1.0243E-02	1.2750E-02
c0	1	1
R ²	8.7900E-01	9.5175E-01
Apparent Cycles (K) at 1 mm Length	463.8	130.0

Table 133. Specimen 30 left side crack growth curve fit coefficients.

R1 (472.7K)			R2 (94.7K)			R3 (75.2K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
277.3	0.0885	2.25	655.3	0.2368	6.02	674.8	0.4026	10.23
205.3	0.0809	2.06	583.3	0.2280	5.79	602.8	0.3951	10.03
133.3	0.0765	1.94	511.3	0.2192	5.57	530.8	0.3328	8.45
61.3	0.0696	1.77	439.3	0.1870	4.75	458.8	0.3182	8.08
0.0	0.0394	1.00	367.3	0.1839	4.67	386.8	0.3168	8.05
			295.3	0.1415	3.59	314.8	0.2500	6.35
			223.3	0.1334	3.39	242.8	0.1924	4.89
			151.3	0.0501	1.27	170.8	0.0916	2.33
			79.3	0.0451	1.15	98.8	0.0885	2.25
			7.3	0.0438	1.11	26.8	0.0627	1.59
			0.0	0.0394	1.00	0.0	0.0394	1.00

Table 134. Specimen 30 right side crack growth details

	R1	R2	R3
c2	-2.2055E-05	-1.9226E-06	-4.5313E-06
c1	1.0344E-02	9.3635E-03	1.7243E-02
c0	1	1	1
R ²	9.2069E-01	9.4874E-01	9.6669E-01
Apparent Cycles (K) at 1 mm Length	472.7	94.7	75.2

Table 135. Specimen 30 right side crack growth curve fit coefficients.

Specimen	Crack Label	Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
-30 (0.475 OHT x 750K) Shot Peen	R1	-15.33	249.44
	R2	-4.75	286.37
	R3	-6.52	93.24
	L1	0.00	264.89
	L2	9.18	293.91

Table 136. Crack angle details for specimen 30.

I. 55% OHT Shot Peened Specimens

Figure 116. Specimen 33 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-33 (0.550 OHT x 1000K) Shot Peen	R3	A	22	55.4	29.9
	L3	A	22	44.5	44.4
	L2	A	22	36.5	69.0
	R2	B	30	65.6	28.1
	R1	C	66	160.9	10.5
	R4	C	66	147.1	12.3
	L1	D	328	435.2	9.3

Table 137. Specimen 33 crack labels and initiation summary.

Figure 117. Specimen 33 left side crack growth since 1 mm vs. cycle count.

Figure 118. Specimen 33 right side crack growth since 1 mm vs. cycle count.

L1 (435.2K)			L2 (36.5K)			L3 (44.5K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
564.8	0.2593	6.59	963.5	0.6151	15.62	955.5	0.6088	15.46
468.8	0.2523	6.41	867.5	0.6137	15.59	859.5	0.5716	14.52
372.8	0.1943	4.93	771.5	0.5565	14.14	763.5	0.5544	14.08
276.8	0.1549	3.93	675.5	0.4768	12.11	667.5	0.4641	11.79
180.8	0.1414	3.59	579.5	0.4202	10.67	571.5	0.3809	9.67
84.8	0.1309	3.32	483.5	0.3942	10.01	475.5	0.3258	8.28
18.8	0.0666	1.69	417.5	0.3757	9.54	409.5	0.3224	8.19
0.0	0.0394	1.00	387.5	0.3351	8.51	379.5	0.3111	7.90
			291.5	0.2494	6.34	283.5	0.2857	7.26
			195.5	0.2280	5.79	187.5	0.2161	5.49
			111.5	0.2068	5.25	103.5	0.1863	4.73
			99.5	0.1463	3.72	91.5	0.1632	4.15
			29.5	0.0817	2.08	21.5	0.0501	1.27
			11.5	0.0646	1.64	3.5	0.0448	1.14
			0.0	0.0394	1.00	0.0	0.0394	1.00

Table 138. Specimen 33 left side crack growth details.

	L1	L2	L3
c2	-9.6653E-06	-7.7231E-06	-5.8871E-06
c1	1.5296E-02	2.2696E-02	2.0597E-02
c0	1	1	1
R ²	9.2876E-01	9.8022E-01	9.7025E-01
Apparent Cycles (K) at 1 mm Length	435.2	36.5	44.5

Table 139. Specimen 33 left side crack growth curve fit coefficients.

R1 (160.9K)			R2 (65.6K)			R3 (55.4K)			R4 (147.1K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
839.1	0.3861	9.81	934.4	0.3596	9.13	944.6	0.5616	14.26	852.90	0.2902	7.37
743.1	0.3543	9.00	838.4	0.3268	8.30	848.6	0.5202	13.21	756.90	0.2113	5.37
647.1	0.3187	8.09	742.4	0.3045	7.74	752.6	0.4519	11.48	660.90	0.1928	4.90
551.1	0.2996	7.61	646.4	0.2193	5.57	656.6	0.4085	10.38	564.90	0.1712	4.35
455.1	0.2678	6.80	550.4	0.1943	4.94	560.6	0.3522	8.95	468.90	0.1261	3.20
359.1	0.1890	4.80	454.4	0.1823	4.63	464.6	0.3440	8.74	372.90	0.1204	3.06
293.1	0.1881	4.78	388.4	0.1800	4.57	398.6	0.2808	7.13	306.90	0.1108	2.82
263.1	0.1303	3.31	358.4	0.1762	4.47	368.6	0.2516	6.39	276.90	0.1099	2.79
167.1	0.0761	1.93	262.4	0.1741	4.42	272.6	0.2034	5.17	180.90	0.0938	2.38
71.1	0.0579	1.47	166.4	0.1122	2.85	176.6	0.1875	4.76	84.90	0.0766	1.95
0.0	0.0394	1.00	82.4	0.1051	2.67	92.6	0.0992	2.52	0.90	0.0398	1.01
			70.4	0.0802	2.04	80.6	0.0794	2.02	0.00	0.0394	1.00
			0.4	0.0401	1.02	10.6	0.0672	1.71			
			0.0	0.0394	1.00	0.0	0.0394	1.00			

Table 140. Specimen 33 right side crack growth details

	R1	R2	R3	R4
c2	-9.4510E-07	-1.0234E-06	-2.8205E-06	2.4047E-06
c1	1.1593E-02	9.3170E-03	1.6516E-02	4.6536E-03
c0	1	1	1	1
R ²	9.7298E-01	9.4610E-01	9.9084E-01	9.5692E-01
Apparent Cycles (K) at 1 mm Length	160.9	65.6	55.4	147.1

Table 141. Specimen 33 right side crack growth curve fit coefficients.

		Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
Specimen	Crack Label		
-33 (0.550 OHT x 1000K) Shot Peen	R1	-6.10	
	R2	-4.01	
	R3	-4.75	
	R4	-4.08	
	L1	3.70	
	L2	9.54	
	L3	8.83	

Table 142. Crack angle details for specimen 33.

Figure 119. Specimen 34 montage with crack labels.

Specimen	Crack Label	Crack Letter	Cycles at Crack Initiation (K)	Apparent Cycles at 1 mm Length (K)	0-1 mm Crack Growth Rate (micron/K)
-34	R1	A	24	72	20.8
(0.550 OHT	L1	A	24	63.5	25.3
x 1000K)	R2	B	26	71.4	22.0
Shot Peen	L2	B	26	71.4	22.0
	L3	C	142	439.5	3.4

Table 143. Specimen 34 crack labels and initiation summary.

Figure 120. Specimen 34 left side crack growth since 1 mm vs. cycle count.

Figure 121. Specimen 34 right side crack growth since 1 mm vs. cycle count.

L1 (63.5K)			L2 (71.4K)			L3 (439.5K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
936.5	0.6119	15.54	928.6	0.5272	13.39	560.5	0.2414	6.13
870.5	0.6101	15.50	862.6	0.5216	13.25	494.5	0.2022	5.14
804.5	0.5735	14.57	796.6	0.4884	12.40	428.5	0.1990	5.06
738.5	0.5452	13.85	730.6	0.4545	11.54	362.5	0.1691	4.30
672.5	0.5136	13.05	664.6	0.4142	10.52	296.5	0.1382	3.51
606.5	0.4867	12.36	598.6	0.3981	10.11	230.5	0.1276	3.24
540.5	0.4301	10.92	532.6	0.3754	9.53	164.5	0.1083	2.75
474.5	0.3823	9.71	466.6	0.3507	8.91	98.5	0.1022	2.60
408.5	0.3424	8.70	400.6	0.3366	8.55	32.5	0.0666	1.69
342.5	0.2629	6.68	334.6	0.2494	6.34	0.0	0.0394	1.00
276.5	0.2493	6.33	268.6	0.2192	5.57			
210.5	0.1980	5.03	202.6	0.1879	4.77			
144.5	0.1468	3.73	136.6	0.1437	3.65			
78.5	0.1108	2.82	70.6	0.1418	3.60			
36.5	0.0929	2.36	28.6	0.0570	1.45			
12.5	0.0828	2.10	4.6	0.0520	1.32			
2.5	0.0417	1.06	0.0	0.0394	1.00			
0.0	0.0394	1.00						

Table 144. Specimen 34 left side crack growth details.

	L1	L2	L3
c2	-5.2256E-06	-6.9495E-06	-3.5059E-06
c1	2.1006E-02	1.9770E-02	1.0659E-02
c0	1	1	1
R ²	9.9414E-01	9.8953E-01	9.6786E-01
Apparent Cycles (K) at 1 mm Length	63.5	71.4	439.5

Table 145. Specimen 34 left side crack growth curve fit coefficients.

R1 (72K)			R2 (71.4K)		
Cycles (K)	L (inches)	L (mm)	Cycles (K)	L (inches)	L (mm)
928.0	0.6075	15.43	928.6	0.5102	12.96
862.0	0.5570	14.15	862.6	0.4640	11.79
796.0	0.5200	13.21	796.6	0.4554	11.57
730.0	0.4781	12.14	730.6	0.4296	10.91
664.0	0.4387	11.14	664.6	0.3828	9.72
598.0	0.4182	10.62	598.6	0.3805	9.67
532.0	0.3728	9.47	532.6	0.3492	8.87
466.0	0.3221	8.18	466.6	0.3336	8.47
400.0	0.3084	7.83	400.6	0.2857	7.26
334.0	0.2303	5.85	334.6	0.2793	7.09
268.0	0.2233	5.67	268.6	0.1706	4.33
202.0	0.1793	4.55	202.6	0.1699	4.32
136.0	0.1484	3.77	136.6	0.1413	3.59
70.0	0.1107	2.81	70.6	0.1186	3.01
28.0	0.0661	1.68	28.6	0.0828	2.10
4.0	0.0501	1.27	4.6	0.0549	1.40
0.0	0.0394	1.00	0.0	0.0394	1.00

Table 146. Specimen 34 right side crack growth details

	R1	R2
c2	-1.9517E-06	-6.0092E-06
c1	1.6985E-02	1.8008E-02
c0	1	1
R ²	9.9520E-01	9.8567E-01
Apparent Cycles (K) at 1 mm Length	72.0	71.4

Table 147. Specimen 34 right side crack growth curve fit coefficients

		Overall Crack Angle (deg)	Crack Initiation Point Angle (deg)
Specimen	Crack Label		
-34 (0.550 OHT x 1000K) Shot Peen	R1	-6.33	
	R2	-5.70	
	L1	9.15	
	L2	8.23	
	L3	2.27	

Table 148. Crack angle details for specimen 34.

ImageJ Macro

```
// This macro creates a series of left/right montages
// The first (right) image is 0000.jpg, 0002.jpg, etc
// The second (left) image is 0001.jpg, 0003.jpg, etc
// The first image is cropped to upper corner FCH,FCV (horiz, vertical)
// and box width and height FBW,FBH (width, height)
// The second is the same except SCH,SCV,SBW,SBH
// Count is the number of the final first (right) image
// scale in various boxes sets scale factor (0.45 currently)
//
// Roger Bradshaw, 1 Nov 04

FCH=80
FCV=392
FBW=2345
FBH=873

SCH=44
SCV=392
SBW=2365
SBH=857

Count=998

// Any part of the montage not set containing an image will have this color
run("Color Picker...");
setForegroundColor(185, 255, 245);
run("Close");
for (n=0; n<=Count; n += 2) {
    if (n < 10) {
run("Open...", "open='C:\\Pictures\\CW170_XX\\000"+n+".JPG'");
makeRectangle(FCH,FCV,FBW,FBH);
run("Crop");
run("Find Edges");
run("Open...", "open='C:\\Pictures\\CW170_XX\\000"+n+1+".JPG'");
makeRectangle(SCH,SCV,SBW,SBH);
run("Crop");
run("Find Edges");
run("Stack Builder");
run("Make Montage...", "columns=1 rows=2 scale=0.45 first=1 last=2 increment=1
border=0 ");
run("Jpeg...", "save='C:\\Pictures\\CW170_XX\\M000"+n+".JPG'");
run("Close");
run("Close");
```

```

run("Close");
run("Close");
    }

    else if (n < 100) {
run("Open...", "open='C:\\Pictures\\CW170_XX\\00"+n+".JPG'");
makeRectangle(FCH,FCV,FBW,FBH);
run("Crop");
run("Find Edges");
run("Open...", "open='C:\\Pictures\\CW170_XX\\00"+n+1+".JPG'");
makeRectangle(SCH,SCV,SBW,SBH);
run("Crop");
run("Find Edges");
run("Stack Builder");
run("Make Montage...", "columns=1 rows=2 scale=0.45 first=1 last=2 increment=1
border=0 ");
run("Jpeg...", "save='C:\\Pictures\\CW170_XX\\M00"+n+".jpg'");
run("Close");
run("Close");
run("Close");
run("Close");
    }

    else if (n < 1000) {
run("Open...", "open='C:\\Pictures\\CW170_XX\\0"+n+".JPG'");
makeRectangle(FCH,FCV,FBW,FBH);
run("Crop");
run("Find Edges");
run("Open...", "open='C:\\Pictures\\CW170_XX\\0"+n+1+".JPG'");
makeRectangle(SCH,SCV,SBW,SBH);
run("Crop");
run("Find Edges");
run("Stack Builder");
run("Make Montage...", "columns=1 rows=2 scale=0.45 first=1 last=2 increment=1
border=0 ");
run("Jpeg...", "save='C:\\Pictures\\CW170_XX\\M0"+n+".jpg'");
run("Close");
run("Close");
run("Close");
run("Close");
    }

    else {
run("Open...", "open='C:\\Pictures\\CW170_XX\\"+n+".JPG'");
makeRectangle(FCH,FCV,FBW,FBH);
run("Crop");
run("Find Edges");
run("Open...", "open='C:\\Pictures\\CW170_XX\\"+n+1+".JPG'");
makeRectangle(SCH,SCV,SBW,SBH);
run("Crop");

```

```
run("Find Edges");
run("Stack Builder");
run("Make Montage...", "columns=1 rows=2 scale=0.45 first=1 last=2 increment=1
border=0 ");
run("Jpeg...", "save='C:\\Pictures\\CW170_XX\\M'+n+'.jpg'");
run("Close");
run("Close");
run("Close");
run("Close");
    }
}
```

VITA

Sarah Gutierrez is a native of Louisville, Kentucky and graduated from Dorothy Sayers Cottage School. She received her bachelor degree in Mechanical Engineering from the University of Louisville Speed Scientific School in December 2004 and has work experience at Boeing Integrated Defense Systems. She will be working for Cummins in Columbus, Indiana.