

CHAPTER 4. EXPERIMENTAL TECHNIQUE

4.1 Corrosion Fatigue under Corrosive Environment with CPC

The experimental part of the project consisting of crack growth test under constant amplitude loading on middle center-crack specimen made of aluminum alloy (2024-T3) are carried out in two stages. One specimen is tested per simulated conditions. In order to study the influence of frequency and stress ratio on the effect of fatigue life with or without the CPC (Corrosion Prevention Compounds), tests are performed at two frequency ratios, 0.5 Hz and 1.0 Hz and two stress ratios of $R=0.2$ and $R=0.5$. LPS 3 Heavy-Duty Inhibitor is used in this study as a CPC. It is provided by LPS Laboratories, Atlanta Headquarters, an Illinois Tool Works Company. The test matrix is given below in Table 4.1.

Table 4.1 Test matrix for corrosive fatigue on fatigue life

	Test Program	Freq. 0.5 Hz		Freq. 1 Hz	
		R = 0.2	R = 0.5	R = 0.2	R = 0.5
Stage 1	Dry air	1	1	1	1
	Water Vapor	1	1	1	1
	CPC + Dry air	1	1	1	1
	CPC + Water vapor	1	1	1	1

The MTS 810 universal testing machine is used to perform the required test. A PC is coupled to the MTS machine to provide constant amplitude loads with MTS TestStar Version 4.0E and Function Generator Version 4.0E software. The crack growth rate is monitored by crack propagation strain gage (TK-CPA01-005). The data is recorded by strain smart (Data Acquisition System). In this study the humid-air tests is performed at around 95 ~ 100% humidity. The humid-air circulates the transparent plastic corrosion chamber. The corrosive environment (humid-air) is produced with *Ultrasonic Humidifier*. The humidifier produces soothing cool mist into the corrosion chamber through clean tube.

Surface analysis and SEM micrograph are conducted on the specimens to understand the mechanism by which CPC affect crack growth. Standard methods for conducting fatigue crack growth tests have been developed, notably ASTM Standard E647. The experimental work involved in data reduction, analysis, plotting of crack growth rate, comparison with literature results are described in detail in ASTM E647 and Saxena, 1996. Crack growth tests are most commonly conducted using zero-to-tension loading, $R = 0$, or tension-to-tension loading with a small R , such as $R = 0.1$. Variations of R in the range 1 to 0.1 have little effect on most materials. Therefore, stress ratio $R = 0.2$ is selected.

4.1.1 Effect of Periodic Overloads on Fatigue Life

The specific objective of this task is to study the influence and interactions of periodic overloads damage on fatigue life on Al-2024-T3. The research focused on the fatigue life and crack growth behavior of Al-2024-T3. By varying the number of low cycle fatigue (LCF), the degree of fatigue damage was changed. This study provides a more reliable basis for fatigue life predictions for various loading conditions. This will also give us recommendations for service life extension and develop improved fatigue life assessment tools.

One major difficulty in fatigue analysis and life assessment for metal is that the commonly used linear cumulative damage law does not always apply for fatigue under varying loading conditions. Since most metal structures are subjected to different loading conditions, the loading history dependence has a profound influence on fatigue life. Also, using SEM, damage could be visualized in the material where the overload occurs. The intended work will include (1) modeling of overload damage during low constant amplitude cycles; (2) modeling of overloading effects on fatigue crack growth; and (3) formulating equations for life time prediction for industrial applications. The test matrix is given below in Table 4.2 to perform the task #2.

Table 4.2 Test matrix for periodic overloads on fatigue life

Spacing cycles between overloads	50	100	200	400	800	2000	4000
OLR = 1.7	1	1	1	1	1	1	1

4.2 Corrosion Fatigue Crack Growth Test Method

Laboratory fatigue test can be classified as crack initiation or crack propagation. In crack initiation testing, specimens are subjected to the number of stress cycles required for a fatigue crack to initiate. In crack propagation testing, fracture mechanics methods are used to determine the crack growth rates of preexisting cracks under cyclic loading. In general, fatigue life testing is stress controlled (SN) or strain controlled (ϵ -N). The test specimens are described primarily by the mode of loading, such as axial stress, plane bending, rotating beam, or alternating torsion. Testing machine is defined by several classifications: (a) the controlled test parameter (load, deflection, strain, twist, torque, etc.); (b) the design characteristics of the machine (direct stress, plane bending, rotating beam, etc.); or (c) the operating characteristics of the machine (electromechanical, servo-hydraulic, electromagnetic, etc.).

Corrosion fatigue tests follow from the ASTM E 606 standard for fatigue testing in air.

The typical cell for corrosion fatigue testing includes an environmental chamber of glass or plastic that contains solution. The specimen is gripped outside of the test solution. The chamber is sealed to the specimen, and solution is circulated through the environmental chamber (corrosion chamber). Due to corrosion chamber, an extensometer cannot be mounted on the surface of the specimen to measure the gage displacement or crack opening displacement. Instead of an extensometer, crack propagation strain gage (TK-CPA01-005) is used in this study to measure the crack growth rate. When fatigue crack growth rate test data are reported for environments, test temperature, pressure of gas, waveform type, waveform frequency, and stress ratio must be reported.

4.3 Parametric Measurement, Computer Automation and Data Analysis

Generally, fatigue processes are historically viewed as cycle-dependent processes, and this approach must be broadened to avoid missing environmental enhancement. Corrosion fatigue testing requires the following recognitions:

- It is important to achieve a steady-state crack growth rate at each test condition, which requires achieving a steady-state surface condition.
- Time dependency is very important, and therefore the role of mean/maximum stress and frequency can be very large.
- Unexpected increases in crack growth rate can occur at specific loading conditions (e.g., associated with achieving critical crack chemistry).

4.4 Crack Propagation Rate (da/dN) versus ΔK Approach to Corrosion Fatigue

While there is a strong reliance on low- and high-cycle fatigue testing, which is designed to characterize stress or strain amplitude vs. cycles to failure, there is an increasing emphasis on characterizing crack propagation using a fracture mechanics approach. This results from the ambiguities associated with defining or identifying crack “initiation”, as well as increasingly successful efforts to unify the two approaches by predicting “initiation” and short crack behavior from a thorough understanding of crack propagation. The advantage of this approach is that corrosion fatigue crack growth (da/dN vs. ΔK) data from testing is in many cases useable in stress intensity solutions for practical prediction of component life.

The fracture mechanics approach isolates crack propagation from initiation and in terms of a precise near-tip mechanical driving force, ΔK . However, the fracture mechanics approach to corrosion fatigue can be compromised by various factors. In addition to the complications arising from crack-tip plasticity (which may affect the assumption of linear, elastic conditions for K) and crack closure effects (which can be accounted for if ΔK_{eff} is known), environmental effects can complicate the requirement of similitude. Another disadvantage of the fracture mechanics approach is that it may not provide a meaningful description of crack “nucleation” especially in cases where cracks are observed to nucleate by processes (e.g., pitting, and corrosion or cracking) that are unrelated to crack advance.

Standard methods of fatigue crack growth (as defined in ASTM E 647) are generally applicable to corrosion fatigue crack growth tests. Some general aspects of corrosion fatigue crack growth are described below, and additional background is provided in *Proc. Int. Symp. On Plan Aging and Life Prediction of Corrodible Structures*, 1995. First, the environment must be contained about the cracked specimen without affecting loading, crack monitoring, or specimen-environment composition. Secondly, load-control and crack-monitoring electronics and environment composition must be stable throughout long-term testing. Thirdly, crack length must also be measured for calculations of stress intensity and crack growth rate.

4.5 Crack Growth Test Methods for Vacuum and Gas

One of the most critical considerations for fatigue tests in vacuum and gaseous environments is the maintenance of the purity of the test environment. Maintaining an ultra-clean test system is important, because even a small amount of impurity can either significantly reduce or accelerate the fatigue crack growth rate, depending on the material and the types of impurity. A clean environmental test chamber that provides a very low background pressure and quantifiable impurity levels (below 10^{-7} to 10^{-6} Pa, or 7.5×10^{-10} to 7.5×10^{-9} torr) is essential, even if the tests are to be carried out in gaseous environments at relatively high pressures (i.e., above the background).

4.5.1 Corrosion Chamber

Stainless steels or plastics are suitable materials for the environmental tests chamber, with copper used as the gasket material. The test chamber usually is equipped with a glass view that enables the operator to visually monitor the progress of the experiment. A complete sealing between specimen and corrosion chamber is needed. High effective seals between plastic and metal surfaces are made with silicon rubber caulking compounds or latex rubber. Since, normal specimen movement or any sudden fracture event should be accommodated without catastrophic consequences. The decision to circulate the environment depends on the application and the extent of any problems in controlling the environmental gases. The corrosion chamber is shown below in Figure 4.1.

4.5.2 Corrosion Environment

Only high-purity, laboratory-grade gases should be used. Additional purification and dehumidification of the gas is recommended by passing it through a molecular-sieve purifier and a cold trap (-196 °C, or -321 °F) before allowing the gas to enter the test chamber. De-ionized distilled water in the reservoir should be purified further while subjecting it to repeated freezing/pumping/thawing cycles in order to remove residual dissolved gases in the water.

The prevailing water chemistry in the environment is an essential factor in any simulation environment. Accelerated fatigue cracking can occur in a number of environments, including seawater, salt water/salt spray, and body fluids. These must be reproduced as closely as possible in the laboratory. Substitute ocean water, as described in ASTM D -

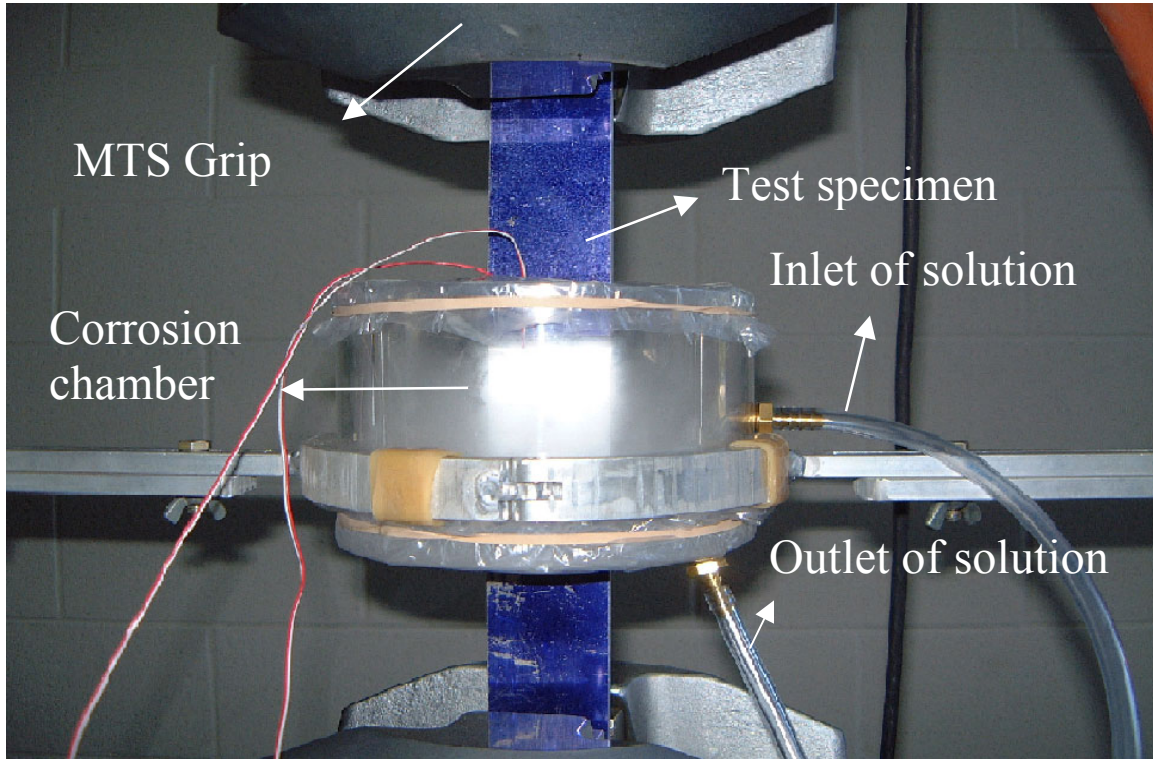


Figure 4.1 Environment chamber with specimen mounted in MTS-810 universal testing machine

1141, usually is a satisfactory substitute for seawater, but in this study, sea-water (3.7% NaCl) is produced by just mixing water with NaCl. Laboratory solutions are prepared using the purest chemicals available in distilled or de-ionized water. Concentrations at the level of parts per million can have profound effects on corrosion. Also, several variables must be measured and controlled when simulating a corrosive environment; solution purity, composition, temperature, pH, dissolved oxygen content, and the flow circulation rate of the solution.

4.6 Analysis of Fracture Surface

It is crucial to ensure accuracy of the crack monitoring technique, to identify branching and out-of-plane cracking, and to determine crack morphology. Accurate determination of crack growth on a cycle or time basis requires an understanding of the resolution of the monitoring technique under the actual test conditions. Fracture surfaces of fatigue-fractured test specimens usually are examined by scanning electron microscopy (SEM) to determine the fracture path and the fracture mode of the test material in relation to its microstructure. Such information is valuable in identifying the fracture mechanism in certain environment and material combinations and is used to assess the severity of the deleterious environment and to aid in analyzing service failures.

Fatigue in inert environments generally produces different fracture modes or fracture paths than does fatigue in deleterious environments. Also, the SEM micrograph is taken

continuously from the crack front initiation to the end of failure. Therefore, the variation of crack surface is investigated in sequence from the crack initiation to the end of crack failure.

A characteristic observation on the growth of macro-cracks is the occurrence of striations on the fatigue fracture surface. The striations are supposed to be remainders of micro-plastic deformations, but the mechanism need not be the same for all materials. Moreover, striations are not observed in all materials. The visibility of striations also depends on the severity of the load cycle. Furthermore, microscopic photography of a macro-crack has shown that the crack front is not a simple straight line and that the crack tip is not necessarily a very sharp crack. The crack tip is rounded. Apparently, the geometry of the macro-crack level does not agree with the classical concept of a crack on elementary fracture mechanics (perfectly flat, straight, or elliptical crack front). However, for these cracks, fracture mechanics applications have been proven to be possible.

4.7 Test Specimen

In-plane yielding must be limited to the crack tip by guaranteeing that the net section stress is below yield strength. Also, the maximum plastic zone size, defined as $\sim 0.2 (K_{\max} / \sigma_{ys})^2$, is much less (e.g., 10- to 50-fold) than the un-cracked ligament. Specimen thickness, as it influences the degree of plane-strain constraint, and crack size, as it influences the chemical driving force, may affect corrosion fatigue crack speeds. Specimen thickness and crack geometry must be treated as variables. Specimen thickness may affect crack growth rate, because transport of the environmental gases to the crack tip may be the rate-limiting factor.

For general economy, compact tension specimens are frequently used. Such specimens minimize the applied load required to achieve a given crack tip stress intensity, thus permitting the use of low load capacity and less expensive test machines. However, due to the unavailability for the compact tension specimen, center pre-crack Al-2024-T3 is used as a test specimen. Center pre-crack tension is also commonly used, because it is relatively easy to maintain the specimen gage section at uniform temperature. As a substantial part of the total fatigue life is attributed to the early state of fatigue crack growth, the crack starter is made by saw cutting at the edge of the center hole. So, crack will start easily at the edges of the hole. Then, the fatigue crack initiation life can be ignored when the fatigue crack growth life is calculated. In corrosion fatigue, the electrochemistry within the crack is mass transport dependent and can vary with crack depth, and possibly also with specimen geometry and with accessibility of solution in the through-thickness direction via the crack sides. These factors can also influence crack growth rates. So, in reports of test data, information regarding crack depth or thickness should be quoted. In addition, in applying load to specimens in a corrosion chamber, chamber friction must not affect load in sealed systems. This is generally not a significant factor in most tests. The geometry and dimension of test specimen are shown below in Figure 4.2.

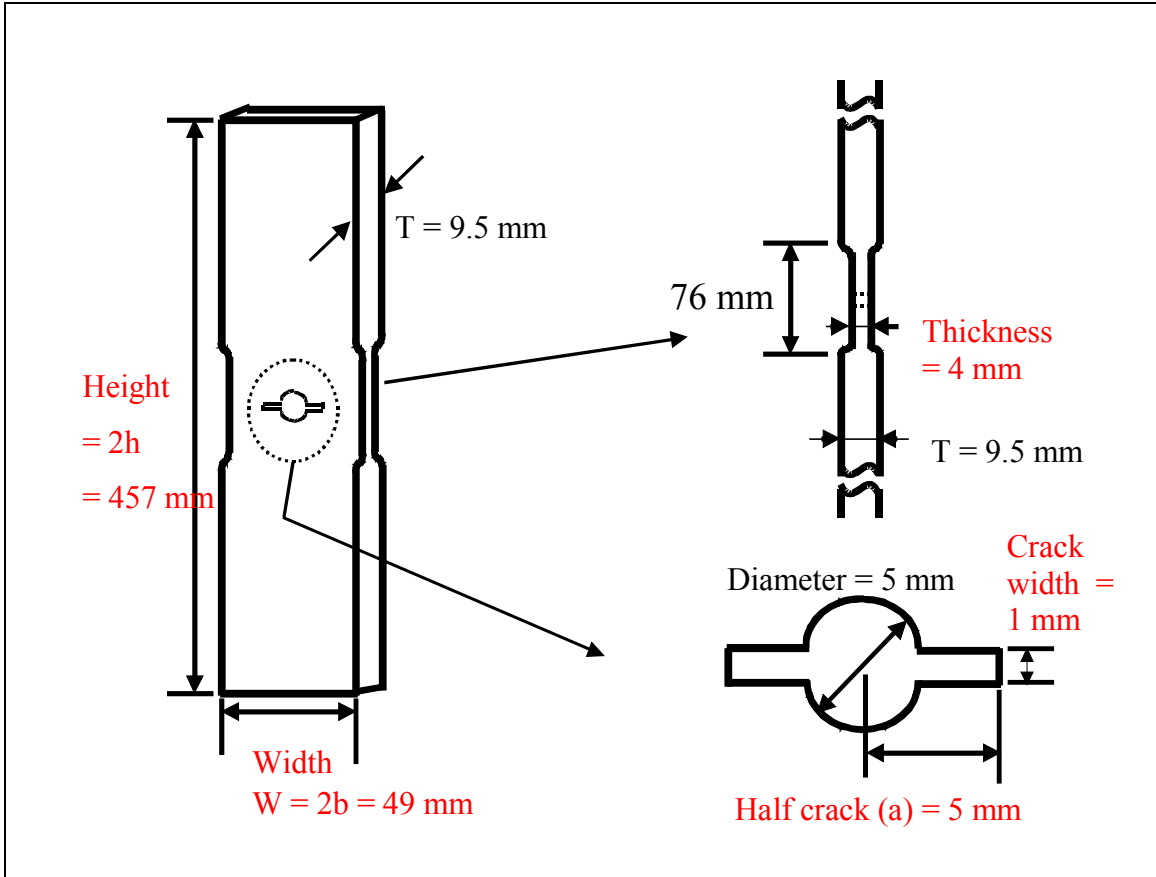


Figure 4.2 Geometry and dimension of test specimen-ASTM E647

4.7.1 Recommendation of Specimen Configuration & Size

In order for results to be valid according to this test method it is required that the specimen be predominantly elastic at all values of applied load. The minimum in-plane specimen sizes to meet this requirement are based primarily on empirical results and are specific to specimen configuration. For the center pre-crack specimen the following is required.

- 1) $(W-2a) \geq 1.25 P_{\max} / (B\sigma_y)$
- 2) $B \leq (W/8)$

where $(W-2a)$ = specimen's un-cracked ligament

W = Width

B = specimen thickness.

For the center pre-crack specimen, the thickness and width is varied independently, which are based on specimen buckling and through-thickness crack-curvature considerations. ASTM E647 recommends that the upper limit on thickness in the center pre-crack specimens is $W/8$. The minimum thickness necessary to avoid excessive lateral

deflections or buckling in the center pre-crack specimens is sensitive to specimen gage length, grip alignment, and load ratio, R. The machined notch for the center pre-crack specimen should be made by electrical-discharge machining (EDM), milling, broaching, or saw-cutting. The recommended width of pre-crack starter slot at the edge of hole is 0.2 mm (0.008 in). To make this pre-crack starter slot, EDM is recommended. Unfortunately, due to the limit of cost, saw-cutting is used. According to ASTM E647, saw-cutting is recommended only for aluminum alloys. So, in this research, the center pre-crack starter is produced by narrow saw. But, the width cannot be made with a width of 0.2 mm. If saw-cutting is used, the minimum width of pre-crack starter slot is 1 mm.

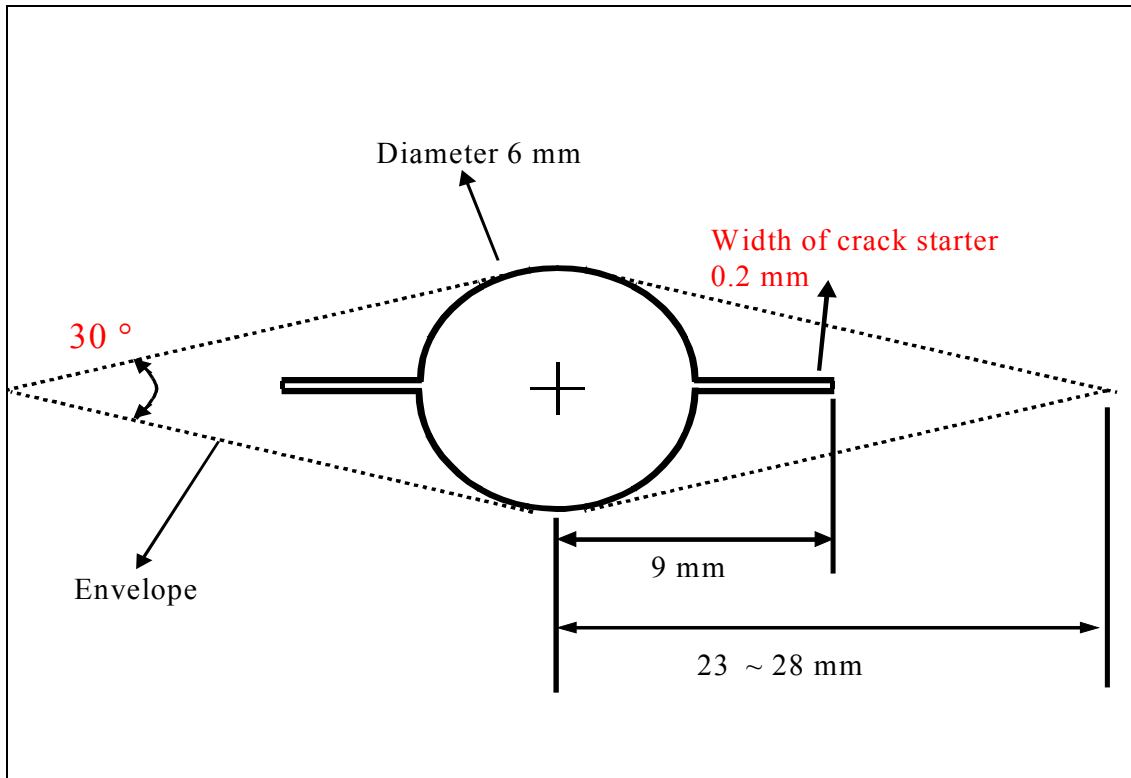


Figure 4.3 Suggested design for center pre-crack starter

The suggested design for center fatigue pre-crack starter is shown below in Figure 4.3. The crack starter must lie within the envelope defined by the 30° included angles having their apexes at the ends of the fatigue cracks. From the basic fracture mechanics, the overall requirement for plane strain is

$$t, a, (b-a), h \geq 2.5 (K/\sigma_y)^2$$

where a = half crack length
b = half width
h = half height

This requirement for plane strain is obviously not met for this case. So, in this research, the state of specimen is between plane-stress and plane strain. As the thickness increases,

the transition happens from the plane stress to plane strain. Also, stress intensity factor K value changes from $K_c = 110 \text{ MN/m}^{3/2}$ (plane stress) to $K_{IC} = 34 \text{ MN/m}^{3/2}$ (plane strain) according to the thickness. For plane stress, ductile fracture mode dominates the fatigue crack growth on the other hand, for plane strain brittle fracture mode dominates the mechanism of fatigue crack growth.

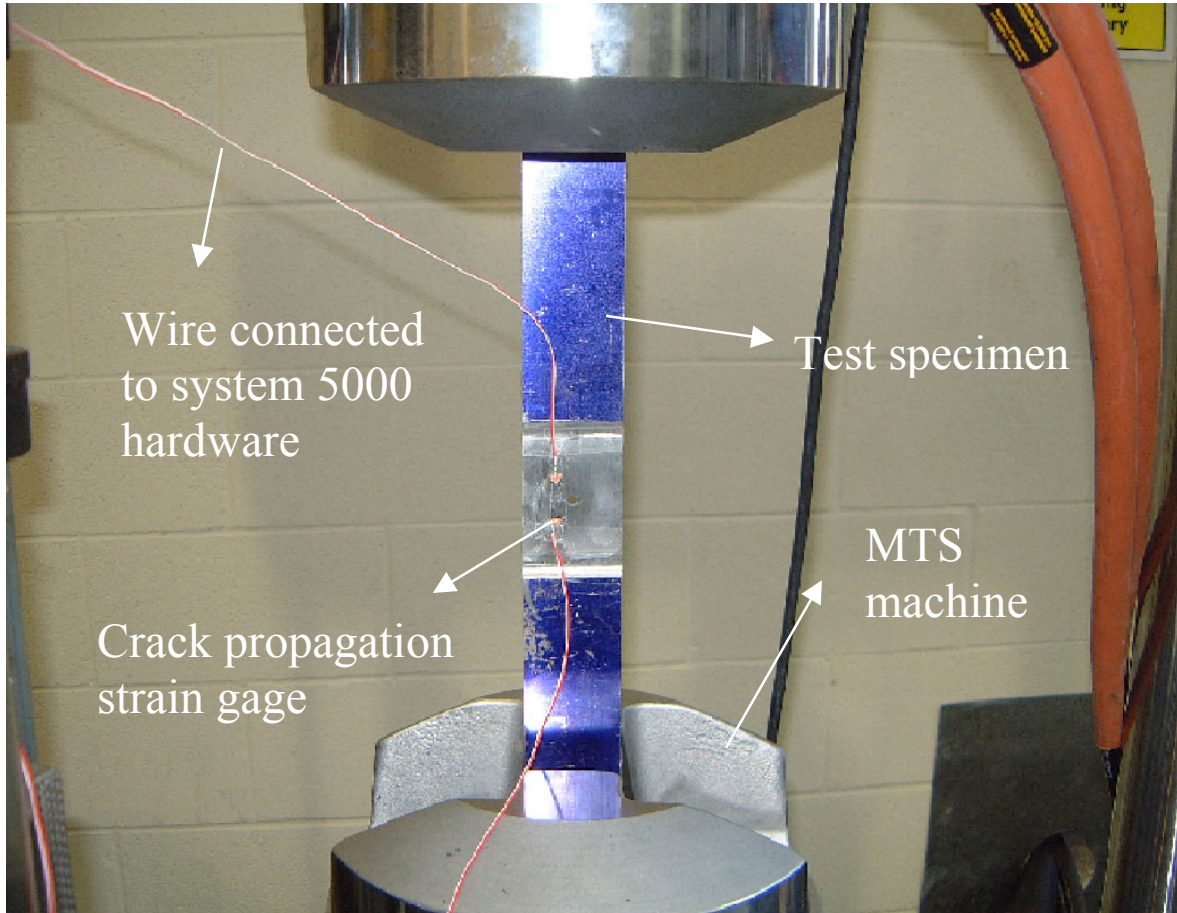


Figure 4.4 Specimen with crack propagation strain gage

4.8 Surface Preparation & Installation of Crack Propagation Strain Gage

The purpose of surface preparation is to develop a chemically clean surface having a roughness appropriate to the gage installation requirements, a surface alkalinity corresponding to a pH of 7 or so, and visible gage layout lines for locating the strain gage. Basically, the surface preparation includes six basic operations. Solvent degreasing, abrading, gage layout lines, conditioning and neutralizing, finally gage bonding. The procedures are given below. GAK-2-200 (M-Bond 200 Application Kits) is used to install the strain gage. Kits are provided from Vishay Micro-Measurements, Inc.

General procedures about surface preparation and gage bonding:

1. Thoroughly degrease the gage area with solvent, such as CSM-1A Degreaser. All degreasing should be done with uncontaminated solvents, thus the use of “one way” containers, such as aerosol cans, is highly advisable.
2. Dry abrading with 220- or 320-grit silicon-carbide paper is generally required. Final abrading is done by using 320 or 400-grit silicon carbide paper on surface wetted with “M-prep conditioner A”. This is followed by wiping dry with a gauze sponge. Repeat this wet abrading process. Then, dry by wiping through with a gauze sponge.
3. Now apply a liberal amount of M-Prep Neutralizer 5A and scrub with a cotton-tipped applicator. Do not wipe back and forth because this may allow contaminants to be deposited again.
4. Place the gage (bonding side down) on a chemically clean plate. Place a 4- or 6-inch (100- or 150-mm) piece of Micro-Measurements No. PCT-2A cellophane tape over the gage. Carefully lift one end of the tape at a shallow angle, then realign the gage/tape assembly properly on the specimen.
5. Lift the gage end of the tape/gage assembly, tuck the loose end of the tape under and press to the specimen surface so that the gage and terminal lie flat, with the bonding surface exposed.
6. M-Bond 200 catalyst can now be applied to the bonding surface of the gage. Set the brush down on the gage and swab the gage backing. Do not stroke the brush in a painting style, but slide the brush over the entire gage surface. Allow the catalyst to dry at least one minute.
7. Lift the tucked-under tape end of the assembly, and holding in the same position, apply one or two drops of M-Bond 200 adhesive at the fold formed by the junction of the tape and specimen surface.
8. Immediately rotate the tape to a 30-degree angle. While holding the tape slightly taut, slowly and firmly make a single wiping stroke over the gage/tape assembly with a piece of gauze. Use a firm pressure with your fingers when wiping over the gage. Firm thumb pressure must be applied to the gage area. This pressure should be held for at least one minute. A very thin, uniform layer of adhesive is desired for optimum bond performance.
9. Remove the tape slowly.

4.8.1 Crack Propagation Strain Gage and Circuitry

Strain gage and circuitry to input of system 5000 hardware is composed of Scanner: Model 5100 Scanner, Sensor Cards: Model 5110 Strain Gage Card and Software: StrainSmart Software provided from Vishay Micro-Measurements, Inc. System 5000 hardware is intended to help measure the strain, temperature, force, displacement and other engineering parameters. StrainSmart software (Version 4.0 Beta) is designed to

function with system 5000 hardware and a variety of measurement sensors. This Strainsmart software also takes into account other parameters, such as temperature, lead-wire resistance, inherent non-linearity in the circuitry. Vishay Micro-Measurements Strainsmart software and System 5000 Hardware is used with crack propagation strain gage (TK-CPA01-005) to monitor the crack growth rate. The connecting the lead-wires from the gage into the signal inputs on the Model strain gage card (Model 5110 strain gage card) is done. This card is located into the slots on the back of the Model 5100 Scanner (System 5000 hardware). A complete measurement system consists of sensor (strain gage) connected to System 5000 hardware, a PC running Strainsmart software (Figure 4.5). Making external connections to strain gage card from the rear end connector is necessary to complete the circuitry. Strainsmart software can be used to obtain a step curve of strands broken versus time. So, Strainsmart is used to monitor a step curve of output due to the increase in resistance with successive broken strands as crack grows through the specimen. The curve can be plotted with time. If the frequency of the test is given, the cycles can be obtained by multiplying with time. For each broken strand, the crack grows 0.01in (0.25mm). There are totally twenty grid lines at each 0.01in (0.25mm) between strands. The increments of crack growth with cycles obtained by the time and frequency can be used to find out the crack growth rate. Until the specimen is broken totally, the time is monitored in order to get the fatigue life cycles.

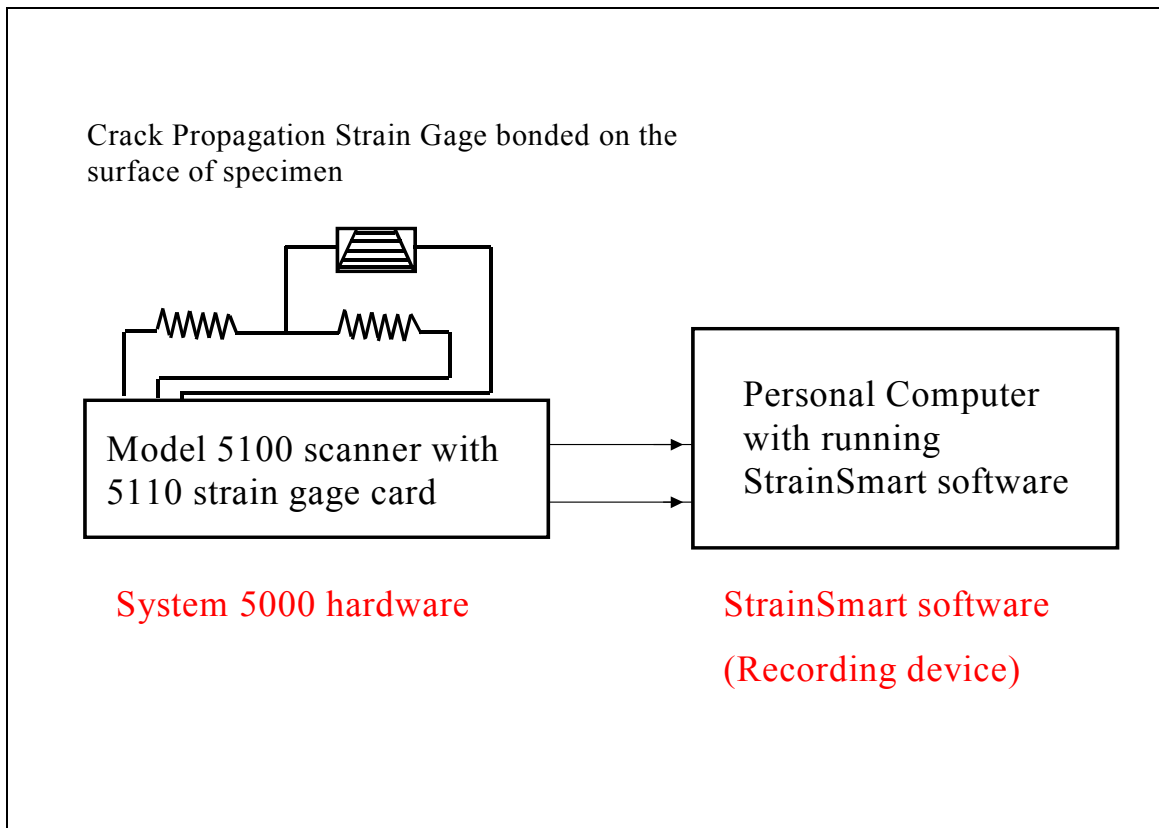


Figure 4.5 Complete measurement system with strain gage, system 5000 hardware & “Strainsmart” software with PC

The details about making the external connections to strain gage card necessary to complete crack propagation strain gage circuitry is shown in Figure 4.6 and 4.7. The setting for strainsmart software is also mentioned below.

1. A uniaxial strain gage should have been selected as sensor with a gage factor 2. The crack propagation strain gage itself has an initial resistance 5 ohm.
2. A wire has been soldered between pins 6 and 2 on the input connector to a 5110 Strain Gage Input Card.
3. Excitation voltage is set to 2V. This input should be connected to a 5110 Strain Gage Input Card.
4. Use foil or wire-wound resistors; not carbon resistor.
5. This circuitry is similar to a quarter-bridge connection.

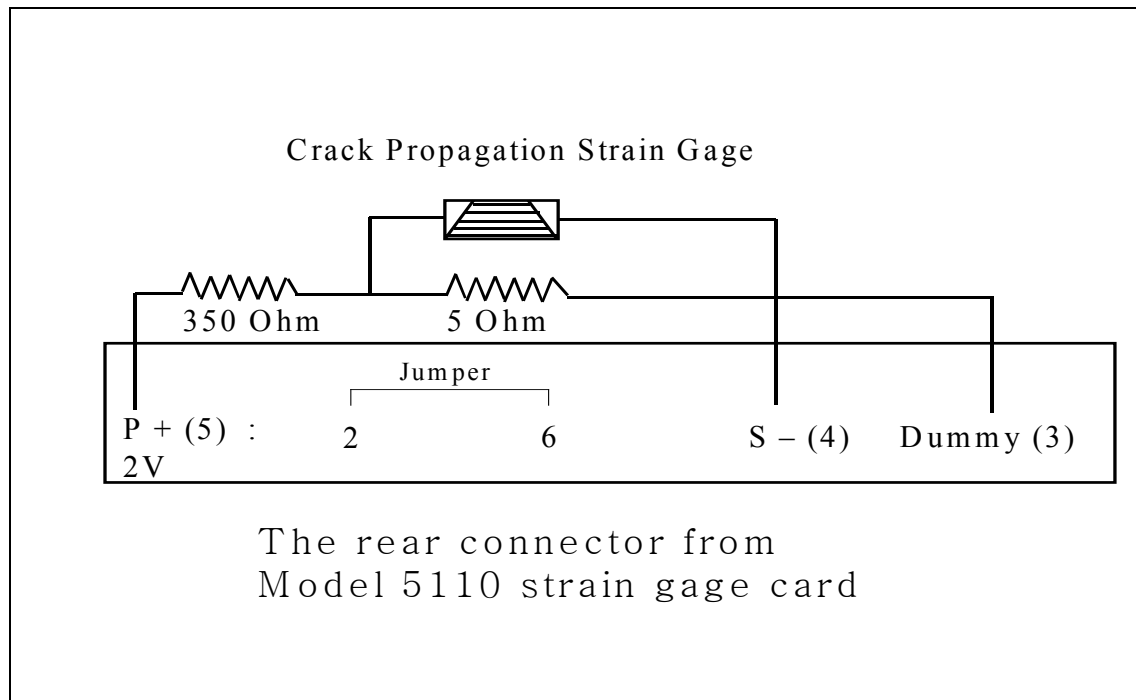


Figure 4.6 External connection to model 5110 strain gage card from the rear connector

4.8.2 Crack Propagation Strain Gage Characteristics

Crack propagation gages have a nominal gage thickness of only 0.0017in (0.043mm). The high-endurance K-alloy foil grid has a single cycle strain range of up to $\pm 1.5\%$ with a fatigue life of greater than 107 cycles at ± 2000 micro-strain. The standard backing is a glass-fiber-reinforced epoxy matrix. The resistance of gage is 5 Ohm when there are no

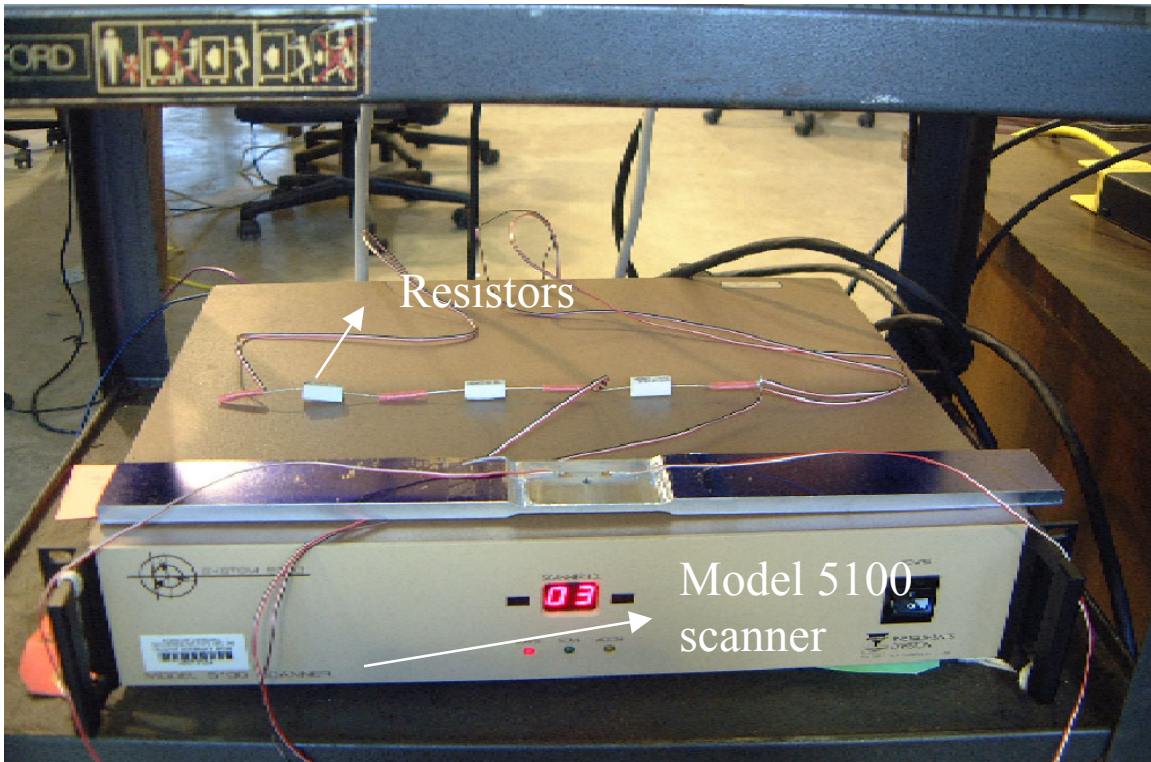


Figure 4.7 Measurement system with strain smart software & system 5000 hardware

fracture strands. Crack propagation gages provide a convenient method for indicating rate of crack propagation in a test part or specimen. The crack propagation gage consists of a number of resistor strands connected in parallel. When bonded causes successive open circuit of the strands, resulting in an increase in total resistance. The CPA01 pattern incorporates 20 resistor strands. The CPA01 produce stepped increases in resistance with successive open circuit (Figure 4.8). Then, due to the increase in resistance, there is a voltage jump for each broken strand. The output is plotted with time. So, we can calculate the cycle (ΔN) by multiplying time with frequency. If the cycle is known, crack growth rate average ($\Delta a/\Delta N$) for each broken strand ($\Delta a = 0.25 \text{ mm}$) can be obtained.

1. Description (CPA 01) - TK-CPA01-005

There are twenty grid lines – 0.01in (0.25mm) between strands. Crack propagation gages have a K-alloy foil grid on a glass-fiber-reinforced epoxy matrix.

4.8.3 Monitoring the Crack Length

Indirect methods, based on specimen compliance or electrical potential technique, have been applied successfully to monitor crack growth. in a wide variety of hostile environments. Visual methods generally are not practical. Visual methods are often precluded from the test chamber. The electrical potential technique is preferred over the compliance method for use inside a corrosion chamber, because the compliance gage is a potential source of test environment contamination. Its use in a corrosion chamber is also unsuitable. However, the electric potential technique is non-contaminating and can be

used in most environments. These methods are described in more detail in ASTM E647 or Andresen, 1996. In this study, crack propagation strain gage (TK-CPA01-005) is used to measure the crack growth rate.

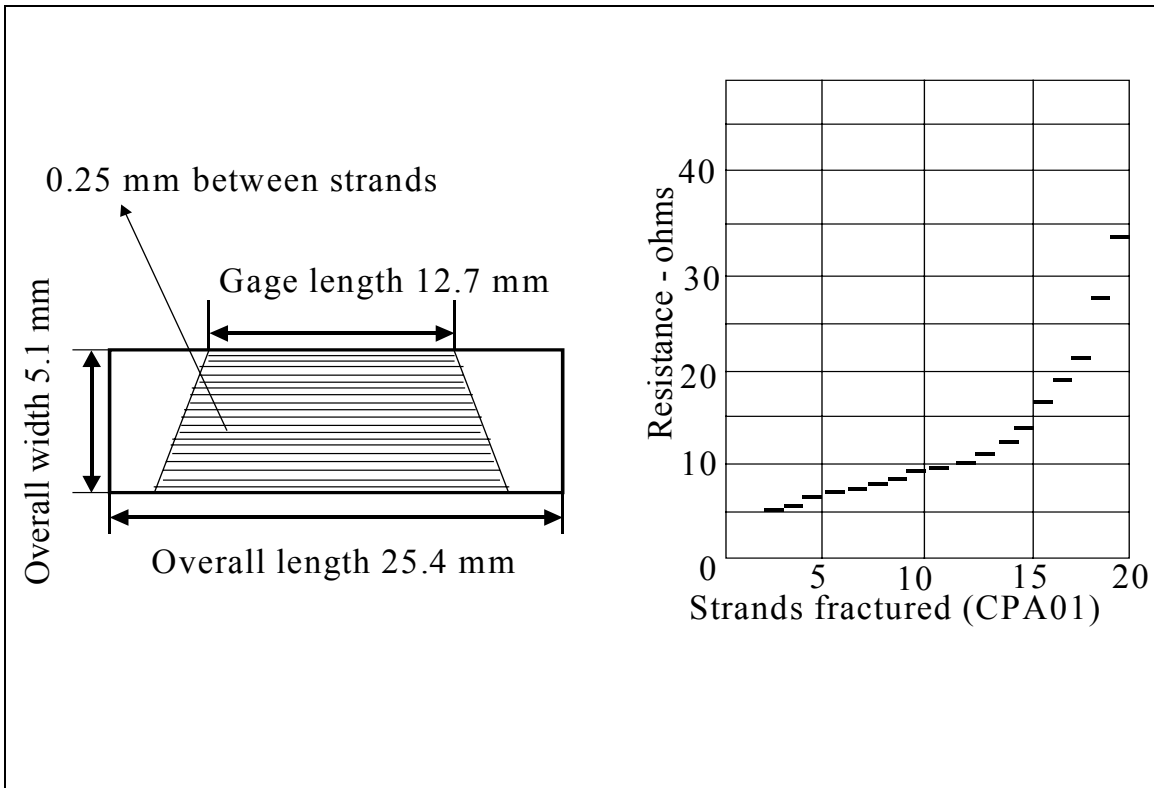


Figure 4.8 Dimensions of crack propagation strain gage and plot of resistance-ohms versus strands fractured

4.8.4 Calculation of Crack Growth

Crack growth rate is calculated from crack length versus cycle number (da/dN) data. Crack growth rate can be calculated by the secant and incremental methods, which are described in ASTM E 647. Another method is, as mentioned above, using Strainsmart. The Strainsmart software is used to monitor a step curve of output due to the increase in resistance with successive broken strands as crack grows through the specimen. The curve can be plotted with time. If the frequency of the test is given, the cycles can be obtained by multiplying with time. For each broken strand, the crack grows 0.01in (0.25mm), because there are twenty grid lines at each 0.01in (0.25mm) between strands. The increments of crack growth with cycles (obtained by the increment time and frequency) can be used to find out the crack growth rate.

4.9 Characteristics of LPS-3 Heavy-Duty Inhibitor (CPC)

As stated above, LPS 3 Heavy-Duty Inhibitor is used in this study. It is provided from LPS Laboratories, Atlanta Headquarters, Illinois Tool Works Company. There are many

kinds of CPC. For example, LPS-2TM and 3TM, Boeshield T-9TM, WD 40TM, CRC 3-36TM, Ardrox 3961TM and so on. But, for multi-year protection and water-displacing properties, LPS 3 Heavy-Duty Inhibitor (LPS 3) is chosen as CPC. The properties are shown below.

1. Multi-year protection
2. Penetrating and water-displacing properties
3. Stops rust and corrosion
4. Provides non-sling lubrication
5. Self-healing, waxy film
6. Provides anti-seize coating

4.10 Experimental Methodology for Overloads Test

Four millimeter thick 2024-T3 is used in this experiment. The tensile strength and yield are reported in literature as 495 and 325 MPa, respectively. The specimen geometry is the center pre-crack specimen, with 457 mm length and 49 mm width. All specimen dimensions are the same like task #1. All specimens were pre-cracked. Load is applied perpendicular to the crack growth direction. MTS closed loop electro-hydraulic testing machine is used to apply loads. A PC is coupled to the system to provide constant amplitude load periodic overloads (TestWare-SX Version 4.0D). Under constant amplitude loading, periodic overloads are applied until a failure. Overload Ratio of 1.7 is used. The periodic spacing cycles between overloads (Figure 4.9) are varied roughly between 20 and 5000. For all tests of Task #2, the stress ratio is 0.2, and the frequency is 0.5 except the periodic overloads. The frequency of overload is chosen as 0.2 due to the hydraulic control error during the demonstration. So, the main objective of task 2 is to find out the optimum spacing cycles between overloads for overload ratio of 1.7 in order to get a maximum fatigue life until failure. Then, the number of cycles for each test required to grow the crack from the initial size to failure is recorded. Overall experimental facility is shown in Figure 4.10.

4.11 Specimen Material (Aluminum alloy 2024-T3)

(1) Mechanical Properties of aluminum alloy 2024-T3

Tensile Strength	Yield Strength	Shear Strength	Fracture Toughness
485 MPa	345 MPa	285 MPa	34 MN/m ^{3/2}

(2) Chemical Compositions Limits of aluminum alloy 2024-T3

Compositions	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti + Zr	Al
Weight (%)	0.5 max	0.5 max	4.4	0.6	0.45	0.1 max	0.05 max	0.2 max	0.2 max	93.5

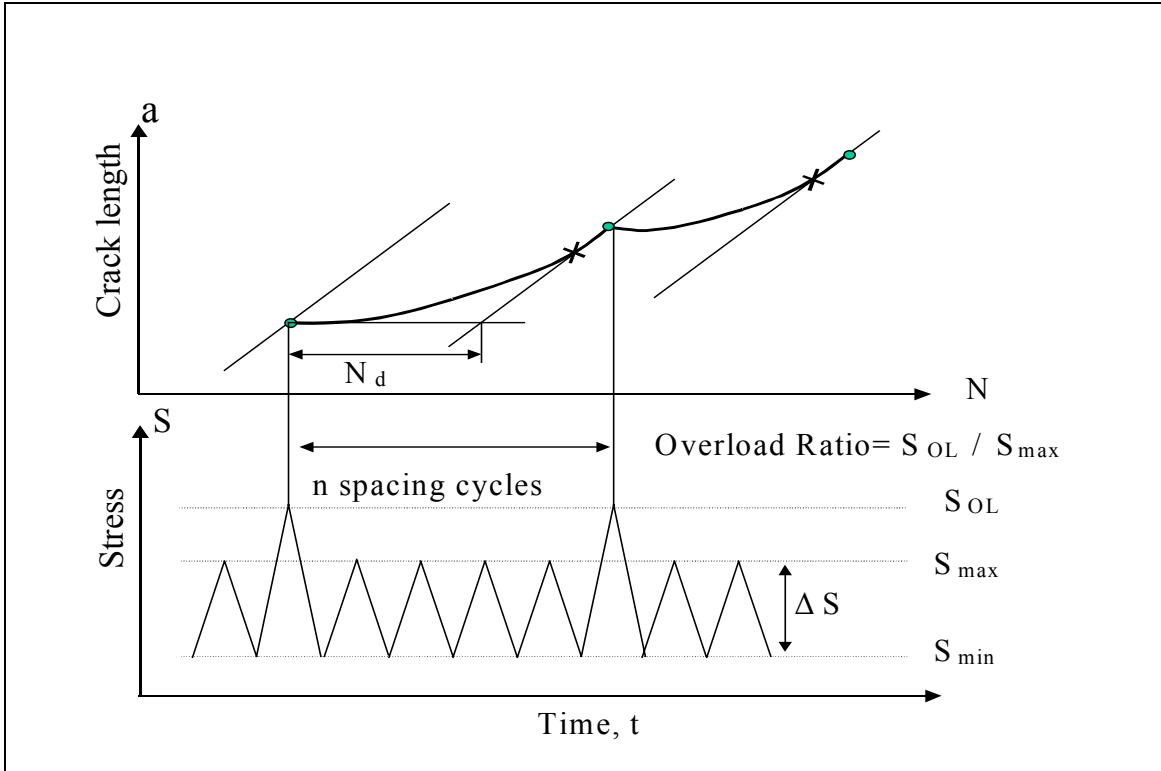


Figure 4.9 Typical behavior of crack length as function of number of cycles at constant ΔS , which results from overloads

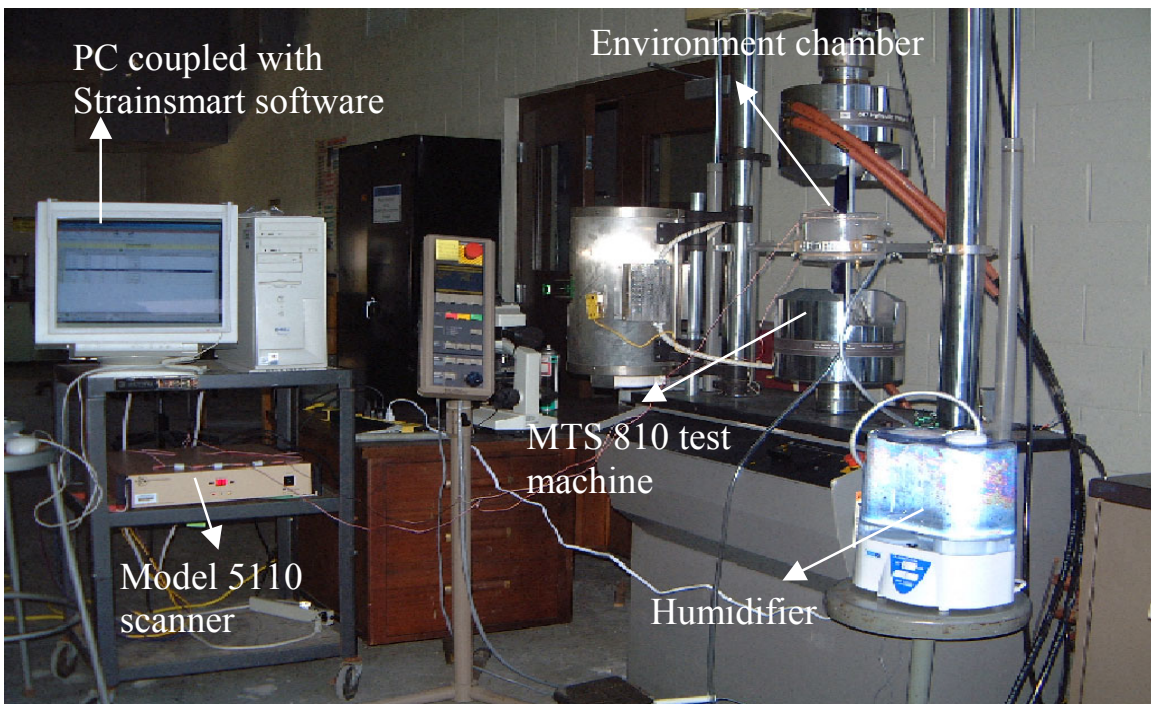


Figure 4.10 Overall experimental facility (MTS-810, Strain smart software, environment chamber)