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EFFECTS OF ENVIRONMENTAL VARIABLES ON THE CRACK INITIATION STAGES OF CORROSION FATIGUE OF HIGH STRENGTH ALUMINUM ALLOYS

FINAL REPORT

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by

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EFFECTS OF ENVIRONMENTAL VARIABLES ON THE CRACK INITIATION STAGES OF THE CORROSION FATIGUE OF HIGH STRENGTH ALUMINUM ALLOYS

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ABSTRACT

This research project was designed to evaluate the effect of environmental variables on the crack initiation stage of corrosion fatigue. The materials studied were six high strength aluminum alloys which are frequently used in the aircraft industry. The research plan was to study fatigue initiation resulting from cyclic loading superimposed on a constant stress. The specimen were exposed in equal increments of atmospheric corrosion between the cyclic stressing so that the initiation of fatigue could be evaluated as a function of corrosion.

In order to obtain the equal increments of atmospheric corrosion, an Atmosphere Corrosion Rate Meter was developed. The ACRM is capable of measuring and recording the corrosivity or rate of corrosion of the atmosphere. A broad range of corrosivity can be measured which include two ranges of environmental conditions, one when the specimen is wet and one when the specimen is relatively dry. The "time of wetness" is also recorded. The Atmospheric Corrosion Rate Meter has the potential of standardizing atmospheric corrosion tests.

For the investigation a test specimen was required which would produce a constant stress on the material to which a cyclic fatigue stress could be superimposed. Such a specimen was developed as the Hole In The Square or HITS specimen. The specimen is capable of developing a constant residual stress to which a fatigue stress can be superimposed. The stress concentrations at the fatigue loading holes limited the life of the specimen during fatigue tests. During the experiments stress corrosion initiated failures were observed.

The tests made at different stress levels revealed that a residual stress as low as 30% of the yield strength would cause stress corrosion cracking in some of the alloys. The stress corrosion susceptibility of the alloys was the dominating factor and obscured any other initiation of corrosion fatigue. The HITS specimen proved to be an excellent stress corrosion test specimen with a self induced residual stress which was easy to duplicate and gave reproducable results.

EFFECTS OF ENVIRONMENTAL VARIABLES ON THE CRACK INITIATION STAGES OF THE CORROSION FATIGUE OF HIGH STRENGTH ALUMINUM ALLOYS

OBJECTIVES

To determine quantitatively the effects of environmental variables on the initiation of corrosion fatigue cracking in high strength aluminum alloys. To predict the corrosion fatigue life using a statistical model derived from atmospheric corrosion data. To provide the designer of aerospace structures with an analytical tool that can be used to prevent corrosion fatigue failures, yet allowing the optimum use of the mechanical properties of high strength aluminum alloys.

INTRODUCTION

Failure analyses of aircraft components reveal that a large fraction of components which cracked apart did so by metal fatigue.[1] The ability to account for fatigue life is broken down into two parts; crack initiation and crack propagation.[2] The development of fracture mechanics in the last two decades has permitted a good understanding of the latter phenomenon.[3] One of the key assumptions usually made is that a given structure will contain a flaw which will allow a crack to begin growing from the time the structure is fabricated and put into service. Actually, this can be an excessive penalty to pay, considering that most aircraft are examined thoroughly before use and then frequently during their lifetime. The problem becomes one of assessing the probability that a surface defect will be the initiation site for the fatigue crack. This most often results from an interaction between the metal and its environment, a process defined as corrosion. The ultimate tool desired is an analytical model of the environment which will predict the time required to initiate a corrosion fatigue crack. Then, coupled with a knowledge of propagation, an accurate predicting can be made of the life of the structure. As examples, such models have already been developed for the pitting

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of aluminum in supply waters,[4] in seawater,[5] and the atmospheric corrosion of low alloy steels.[6]

In order to assess the present position with high strength aluminum alloys, a review of the literature was made. While a large amount of information is available for the standard aircraft alloys, such as 2024, 7075 and 7079, they are being replaced in the newer designs by 2124, 7475 and 2219. These latter alloys are tougher, largely due to a lowered content of intermetallics. Unfortunately, this alteration in composition tends to make the alloys more susceptible to deep isolated pitting in place of the fine, widely scattered superficial attack characteristic of the behavior of the older alloys. Therefore, it is highly important that a study be made of such failure mechanisms as corrosion fatigue, since deep, isolated pits are generally conceded to be more serious crack starters than shallow, well distributed ones.

As reported in a ASTM symposium,[7] several programs involved with long term atmospheric corrosion studies are being completed. Scientists are able to define the environmental parameters causing corrosion problems. The data from environmental studies, plus the emphasis being placed on air quality has provided impetus for the detailed analysis of atmospheric corrosion phenomena.

Some years ago, one of the investigators was responsible for testing large numbers of stress corrosion specimens in the atmosphere. Many of these were exposed on the roof of our laboratory building. One of the technicians noted that he always had a rash of failures after it had rained. These failures, by the way, were taken at the time of first appearance of a crack under low power magnification. Consequently, the parameter measured was crack initiation and not total life which would have included a significant fraction of propagation time.

This instance is cited to support a major assumption in this work; that the corrosive agent causing stress cracking is <u>water</u> (fully aerated, of course). The amount of dissolved solids is less significant as only a few parts per million of chloride ion, for example, will cause pitting attack on aluminum. Chlorides are not even necessary to produce stress corrosion cracking as found several years ago.[8] Thus, the major environmental parameter to be studied is that known as "time-of-wetness". Sea salt tends to prolong this period due to its hygroscopic nature. Thus, a marine atmosphere does tend to be more corrosive than an inland, but equally wet climate. Temperature, of course, also has an effect but in the range of ambient temperatures of interest, it primarily shows up in the rate expression and does not control the initiation stages.

A second major assumption is that most structures are under a static stress most of the time to which cyclic stresses are added during random periods of use. See Figure 1, taken from Anderson's work.[9] Therefore, it is permissable to study the initiation of corrosion fatigue cracking using an intermittant cyclic loading on top of a static stress.[10] The problem becomes one of judicious choosing of stress levels, so that the fatigue process is not unduly hurried and yet the corrosion fatigue component is not entirely masked by either stress corrosion cracking or failure under loading due to loss in net section area by pitting. This latter phenomenon is a problem with some of the smaller stress corrosion specimens in common use today.

TEST SPECIMEN

To fully evaluate the material, a test specimen was necessary which would duplicate the actual condition of stress and corrosion to which the material is subjected during use. These conditions are 1) a constant stress, 2) a superimposed alternating stress and 3) a corrosive atmosphere. The stresses could be applied to any part of the metal but for aluminum the most critical orientation for stress corrosion is normal to the rolling plane in the short transverse direction in the plate.

There are many standard tests and test specimens for subjecting a metal to stress and corrosion as indicated in ASTM Standard G30, G38 and G39[11]. These tests are designed for constant levels of stress or stress intensity. While alternating stresses could be superimposed, the retention and evaluation of the constant stress component would be difficult.

CONSTANT STRESS SPECIMEN

In 1971, Anderson [9] presented a concept of a self-stressed stress corrosion specimen. This concept, based on a SCC ring specimen, was designed as a square specimen with a round hole in the center. He suggested that if the specimen was compressed until it plastically deformed, a residual tensile stress would be retained after the load was removed. Initial experiments with a specimen of this type showed that a residual tensile strain was produced in the specimen when compressed, but the strain (and presumably the related stress) was developed in the sides normal to the compressive load and not in the sides which were compressed, as he had postulated.

To determine if the hole-in-the-square (HITS) specimen would be suitable as a constant test specimen, a series of experiments were run to determine the stress distribution on the surface of the specimen and to evaluate the residual tensile stresses retained when the compression load was removed.

From these tests it was concluded that the HITS specimen makes an excellent constant stress specimen with reproducable and predictable residual stresses. The residual stress is a tensile stress on the inside surface. The specimen can perform as a stress corrosion type specimen or as a preload specimen.

A description of these tests and their results is presented in the First Progress Report dated 1 February 1970.[12]

An alternating stress can be superimposed on the residual stress by adapting the specimen to a fatigue machine. Eight one-quarter inch holes were drilled in the specimen as shown in Figure 2 for adapting specimens to the fatigue machine. Holes were located in areas which had not been plastically deformed. The capacity of the fatigue machine was 5,000 pounds. A small tensile load was required as a minimum alternating load to keep the machine and specimen steady. Therefore, loads of 400 to

4000 pounds were selected as the minimum and maximum loads on the fatigue machine. Based on the 0.750 square inch area, the maximum tensile stress superimposed on the static stress was 5300 psi.

The limiting factor on many of the test specimen was failure of the specimen at the fatigue loading holes. About 50% of the specimen failed prematurely which precluded a true evaluation of the alloys under fatigue conditions.

Of the specimen which did not fail in the fatigue loading holes, only those specimen which developed stress corrosion cracking failed during the test. The sequence appeared to be SCC cracking and then propagation of the SCC crack during the fatigue loading. No evidence was observed where pitting initiated fatigue cracks. The premature failure of the loading holes may have eliminated this type of fatigue.

To verify the HITS specimen as a SCC test specimen, a series of tests were made under SCC conditions. Of primary concern was the effect of residual stress on the reaction of the specimen. Two aluminum alloys were selected for these tests: 2024 T351 and 7075 T7351. The mechanical properties of these alloys were determined as follows:

Alloy	Orientation In Plate	Strength Tensile Ksi	Yield Strength Ksi	Modulus of Elasticity Psi x 10^6
2024 T351	Short Transverse	57.8	45.0	9.33
2024 T351	Transverse	67.2	47.6	10.15
2024 T351	Longitudinal	68.3	54.0	9.80
7075 T7351	Short Transverse	70.7	60.0	10.90
7075 T7351	Longitudinal	75.1	67.0	9.25

As described previously [12], HITS specimens were selected for testing using the selected orientations in the 3 inch plates as shown in Figure 3. Strain gages were used to measure strain and stress in the specimen. They were attached as shown in Figure 2 and loads applied as indicated. Loads were applied to produce residual stresses in the specimen as a percentage of the alloys yield strength. The result of load vs. the residual stress is shown in Figure 4. To insure that the test leg of the specimen was not loaded beyond the elastic limit, the test specimen was sectioned after the final loading. Once sectioned, the residual stress returned to zero as was found in the original tests which were previously reported.

HITS specimens of both alloys were loaded to produce residual stresses of 0, 15, 30, 45 and 60% of the yield strength of the alloy. The first series were exposed up to 55 days to the atmosphere at the previously described test racks near Biscayne Bay. Results of these tests were as follows:

Alloy: 2024 T351
Environment: Ocean Front Atmosphere
Orientation: Short Transverse Stressed Direction

S/N	Percent of YS	Applied Load (lb.)	Residual Stress (psi)	Visual Observations
F75	0	0	0	Light corrosion in 8 weeks
F74	15	35200	6750	Light corrosion in 8 weeks
F65	30	42000	13500	SCC in 3 weeks
F66	45	47500	20250	SCC in 3 weeks
F69	60	52000	27000	SCC in 3 weeks

Alloy: 7075 T7351
Environment: Ocean Front Atmosphere
Orientation: Short Transverse Stressed Orientation

S/N	Percent of YS	Applied Load (lb.)	Residual Stress (psi)	Visual Observations
C57	15	46500	9150	Light corrosion in 8 weeks
C51	30	54000	18000	SCC in 4 weeks
C52	45	60000	27000	SCC in 4 weeks
C61	60	68000	36000	SCC in 4 weeks

To determine the effect of sea water on the test specimen, a second series of specimen were loaded and immersed in fresh flowing sea water. The average temperature of the sea water was 23°C. The results were as follows:

rate — was incorporated in the meter so that "time of wetness" could still be evaluated. Several modification were also made to the sensor to improve its response and accuracy. Tests made with the sensor in an enclosed chamber and when exposed to outdoor atmosphere near salt water resulted in excellent correlation between the counts recorded by the meter and the atmospheric conditions of relative humidity, temperature, rain (wetness) and chlorides (as measured by a salt fall gage). In addition, short term corrosion tests on several aluminiun alloys indicated an excellent correlation between rate meter counts and weight loss for each alloy. Details of the development of the design and testing of the sensor and the corrosion rate meter are presented in the Second Progress Report dated February 1, 1979.[16]

One of the projected applications of the corrosion rate meter was to evaluate the corrosion environment of aircraft. To accomplish this a completely portable unit was designed. Mark III was designed for battery operation with all components selected for minimum current drain. The meter would sample the corrosion current at selected periods and store the information. The last two meters, Mark IV and Mark V, were the final products. They were fully enclosed with LED readout thru a window with monantary on switches used to call for retrieval of data and to momentarily turn on the LED's. Three buttons were used one for high count data, one for low count data and one for time of high count (time of wetness).

Initial calibration of the instruments showed inconsistant results. After final adjustments and recalibration all meters produced consistant results. A description of the final design of the meter including the mathematics of the counting sequence is given in the Second Progress Report [16] and described below. This design produced a meter which was portable, easily read and depending on frequency of corrosion rate count could operate portable for two to six months.

Alloy: 2024 T351
Environment: Sea Water
Orientation: Short Transverse Direction

S/N	Percent of YS	Applied Load (lb.)	Residual Stress (psi)	Visual Observations
F73	15	35200	6750	Light pitting in 8 weeks
F64	30	42000	13500	SCC in 3 weeks
F70	45	47500	20250	SCC in 3 weeks
F67	60	52000	27000	SCC in 3 weeks

Alloy: 7075 T7351
Environment: Sea Water
Orientation: Short Transverse Direction

S/N	Percent of YS	Applied Load (lb.)	Residual Stress (psi)	Visual Observations
C60	0	0	0	Light corrosion in 8 weeks
C59	15	46500	9150	Light pitting in 8 weeks
C50	30	54000	18000	SCC in 2 weeks
C53	45	60000	27000	SCC in 2 weeks
C56	60	68000	36000	SCC in 2 weeks

Alloy 2024 T351 stressed in the longitudinal direction gave the following results when exposed in sea water:

Alloy: 2024 T351
Environment: Sea Water
Orientation: Longitudinal Direction

S/N	Percent of YS	Applied Load (lb.)	Residual Stress (psi)	Visual Observations
F68T	30	45000	16200	SCC in 4 weeks
F79T	60	54000	32400	SCC in 4 weeks

From these tests it was concluded that the HITS specimen performed perfectly as a stress corrosion test specimen. The minimum residual stress to cause cracking in these two alloys was between 15% and 30% of the yield strength whether in the atmosphere or in sea water.

ATMOSPHERE CORROSION RATE METER

The original concept of this project was to expose high strength aluminum alloys to alternate corrosion and fatigue conditions. Because of the uncertainty of both corrosion and fatigue initiation, an attempt would be made to use equal increments of corrosion. Because the most active corrosion occurs while the specimen are exposed to an electrolyte, the "time of wetness" concept would be used and if specimen were exposed to equal time of wetness periods they should be exposed to equal corrosion [13]. The original concept of a corrosion measuring instrument was to use a zero resistance current meter as a simple current integrator connected to a galvanic cell which would produce current when wet and thus measure time of wetness. The original meter produced poor resolution. Aluminum has low corrosion rates in the atmosphere and thus a high degree of sensitivity is required if accurate corrosion time is to be measured. When the redesigned galvanic cell was in the wet condition, it produced too much current and destroyed the recording elements in the Curtis meter.

To find an instrument which would over come this limitation, a review of available instruments used for corrosion evaluation was made [14][15] and a design similar to one used by Kucera and Mattsson [14] was selected. The instrument constructed proved to be satisfactory and measured and recorded corrosion rates over a very wide range. A total of five instruments have been constructed based on this design. Mark I was electro-mechanical in design and closely followed the design of Kucera and Mattsson. Two count ranges were utilized and the upper limit on each was the response time of the relays which operate to activate the counters. To overcome this and improve the accuracy of the meter, a new design using all solid state electronics was made. Mark II like Mark I was a laboratory unit which operates on 115 volts AC power. This eliminated the response limitation of mechanical relays and counters. The concept of two ranges of corrosion — wet or fast corrosion rate and not wet or slow corrosion

Corrosion Rate Meter — Final Design

The final design consisted of two units, the sensor, which is placed in the environment to be evaluated and the meter which is connected to the sensor by two shielded wires. The meter can be at any location for ease in reading.

The Sensor

The sensor used with the corrosion are basically a copper-aluminum cell. It is constructed from 4 inch square aluminum and copper plates .050 inch thick. The sensor has alternating copper and aluminum plates insulated with 0.004 inch double stick Teflon tape between the plates. There are four plates of copper and four plates of aluminum. All four aluminum plates are connected with one brass bolt, and the copper plates are connected with a second brass bolt. The bolts are the electrical contacts.

A hole 2" in diameter is drilled in the center of the plates. The entire sensor is insulated from the atmosphere except the area of the hole. This insulation is obtained by acrylic laquer on the flat surfaces and liquid plastic on the edges and electrical contact bolts. This configuration was designed to match the corrosion specimen (THIS) with the same area exposed to the environment and the same exposure geometry.

The Meter

The assumption is made that the current-time integral of the output of the sensor will be proportional to the amount of corrosion. Early models of the atmospheric corrosion rate meters have evaluated this integral by actual integration of the current and then rezeroing the integrator. The problem with this approach was the relatively large power requirements of this continuous integration. The portable, battery operated models operate by a periodic sample of the current and summing the values of current measured.

To meter logic diagram is shown in Fig. 5. There are several main sections of the meter as described below.

The input from the sensor goes directly to the current to voltage amplifier. The sensor is considered to be a current source. The current to voltage amplifier acts like a zero resistance ammeter with the voltage output equal to 10^4 time the sensor output. This section is operational at all times so that the sensor always sees a short circuit on its output. The current requirements for this section are 20 A from the $\pm$12 volt supplies.

The next section is the high-low range comparator. The high range has been determined by previous tests to be about 1 MA output from the sensor. There are three main characteristics of this comparator. The reference voltage for the threshold is set by an offset voltage trim pot. The output is limited to +12 volt and minus 0.2 volts by a zenor diode in the negative feedback circuit. There is a resistor in the positive feedback circuit to give 1 mv hysteresis. This circuit is always on as the current needed is only 20 microampere.

The control section of the meter controls the sample interval and sample time. It is driven by a 4,096 Hz clock. There is a manual sample interval control. This allows the user to program the sample interval at 5 min., 10 min., or 20 min. The outputs from this section are as follow:

A control line to the switchable regulated power supply goes low when power is needed for the voltage-frequency (v-f) converter. The v-f converter draws 6 ma during operation and needs a regulated supply. The high power requirements of the v-f is the reason for the switchable supply.

After the power supply and v-f converter are allowed to stabilize for .5 sec., the sample interval is outpout. This controls the length of time in which the output of the v-f converter is counted. The high-low range signal tells the gating control section to channel the output from the v-f converter to the low range accumulator, if necessary.

The last section of the meter is the accumulator and data output section. Both the low and high range accumulators have six digits. The high time accumulator has three digits. The manual output control signals the demultiplexer as to which accumulator to output to the LED display. The manual output control consists of three momentary push button switches. One button for each of the accumulators. When one of the push button is depressed thre functions are implemented. First the multiplexed output, of the accumulators are activated. By not having the accumulator outputs active at all times gives a 25% savings in standby current. The second function of the push button is to select the desired accumulator. The third function is to activate the LED display. The LED uses a separate battery. The current draw is about 60 ma during display and zero when deactivated.

The battery supply section (not shown in the diagram) consists of three 500 ma-hr 12.6 volt batteries. Two of the batteries are used for the +12 volt supply. They are connected in parallel and each battery is protected by a diode. The current drawn from the positive supply is about 450 microampere during standby and 600 microampere during data output, and 6 ma during acquisition. With the meter in the 5 min. sample interval mode the positive supply batteries will last at least two months.

The -12 volt supply has a single 500 ma-hr 12.6 volt battery. This battery also has a diode in series with it to equalize the positive and negative supplies. This battery will probably last about 1.5 years as the current drawn is only 40 microampere.

Summary and Conclusions

This project has been carried out over a period of 5 years and under the direction of two principal investigators. Two of the objectives of the project were never fully obtained. The effect of environmental factor on the initiation phase of corrosion fatigue under static and alternating stresses was not achieved. Neither was a statistical model to predict corrosion fatigue life. These objectives were incompleted because of the premature failure of many specimens due to simple fatigue and because of the overriding factor of stress corrosion cracking in these alloys.

This project did have, however, two major accomplishments. The first was the development of a self induced stress specimen for stress corrosion cracking. The specimen provided a test specimen in which a controlled amount of residual stress could be induced which was easy to machine and which gave reproducible results. With modifications, the specimen could be made adaptable for its original purpose of a preloaded specimen for corrosion fatigue.

The second accomplishment of this project was the design and construction of a portable meter designed to measure and record the corrosivity of the atmosphere. The meter not only measures the "time of wetness" but measures the degree of corrosivity during the "dry" time and during the "wet" time. The meter can be used at any location to evaluate the environment for degree of corrosion exposure. Applications are many but it could be used to measure corrosion of a component which has a known corrosion life or it could be used to monitor the environment of a component under unknown or severe corrosion conditions.

The meter, once standardized, has the potential of being able to compare the corrosivity of the atmosphere at different locations at different times. This could lead to more standardized corrosion tests and correlation between atmospheric corrosion data at different locations.

ACKNOWLEDGEMENTS

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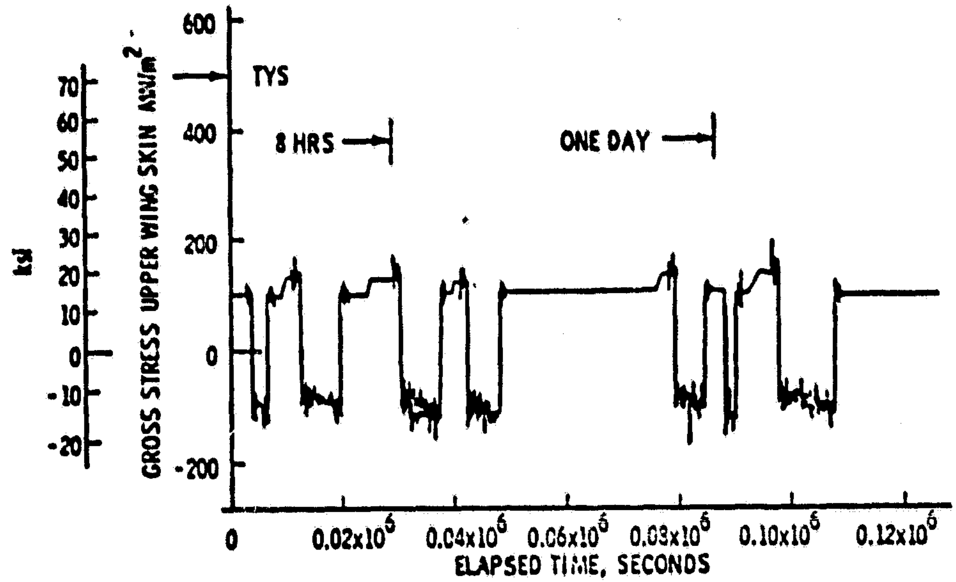

FIGURE 1. Diurnal Gross Stress History of Upper Wing Skin Section.

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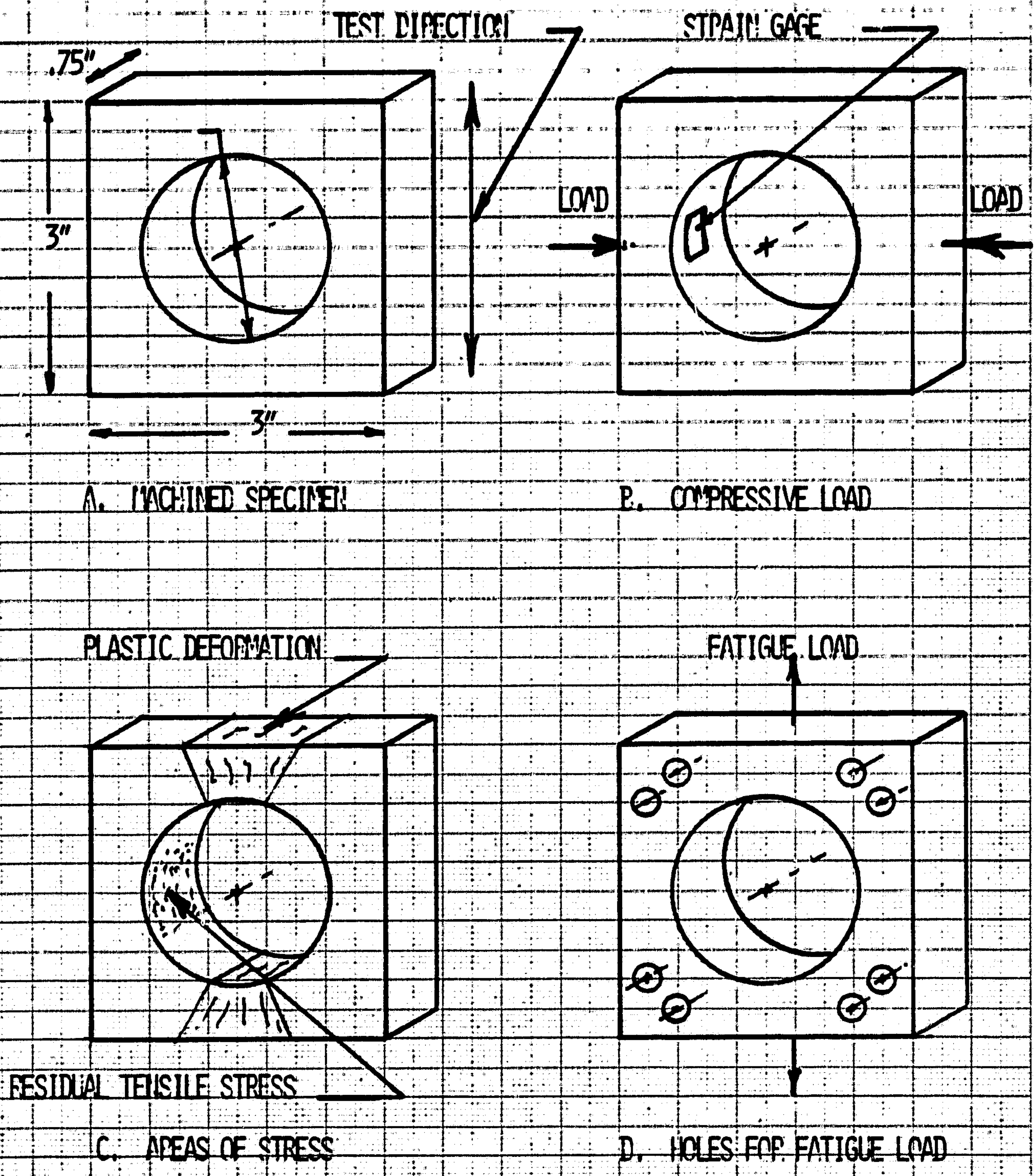

FIGURE 2. HITS TEST SPECIMEN

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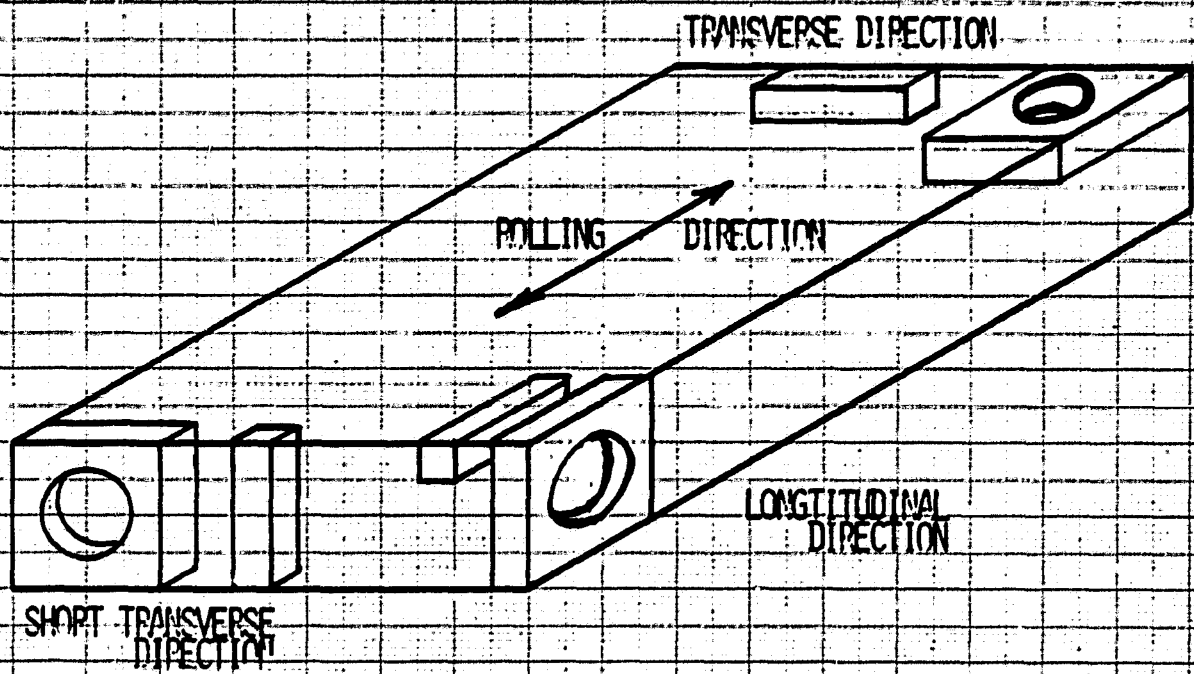

FIGURE 3. ALUMINUM PLATE SHOWING ORIENTATION OF HITS TEST SPECIMEN AND TENSILE SPECIMEN

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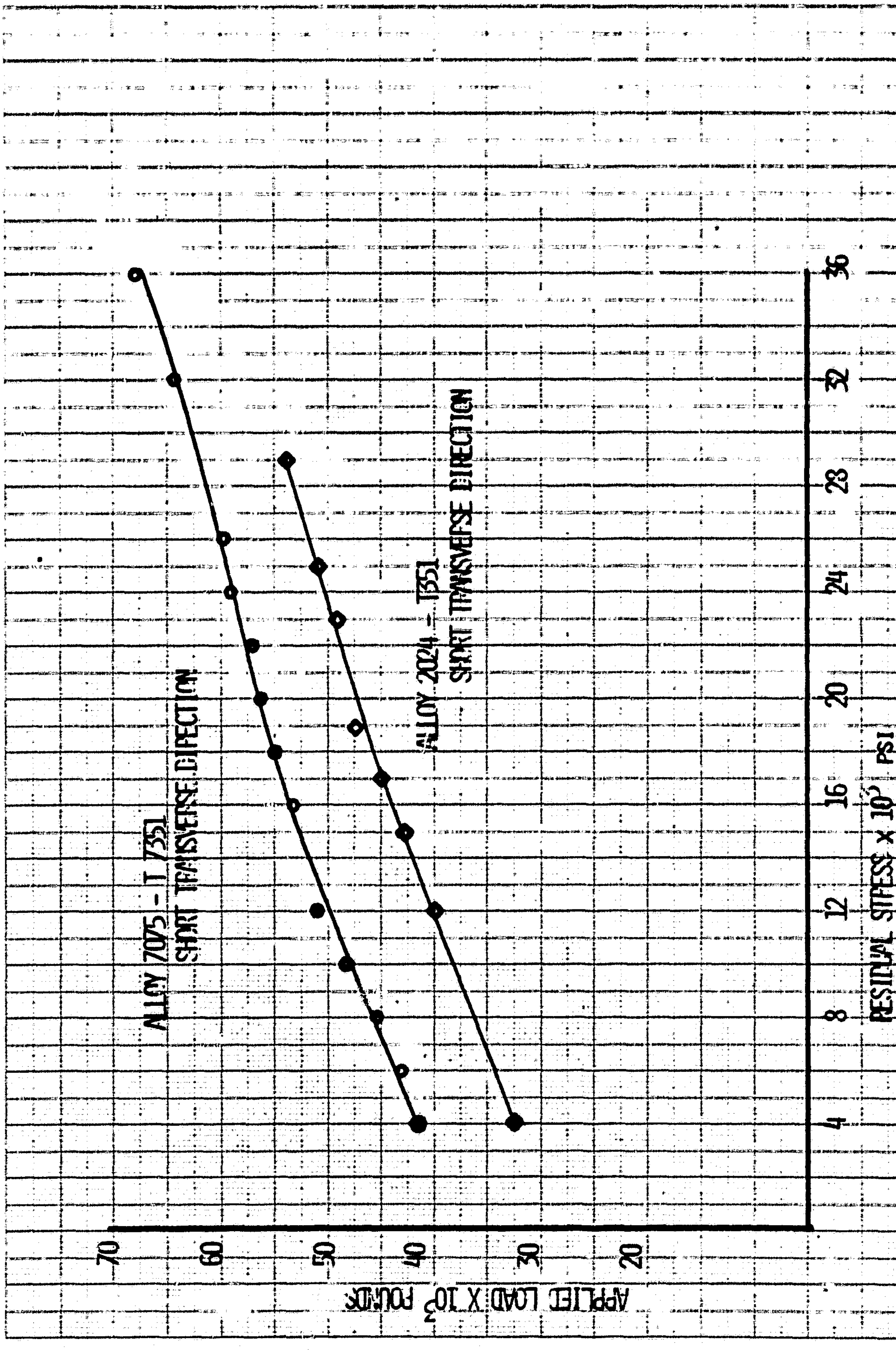

FIGURE 4. APPLIED LOAD VS RESIDUAL STRESS IN HETS SPECIMEN

ATMOSPHERIC CORROSION RATE METER

FUNCTION DIAGRAM

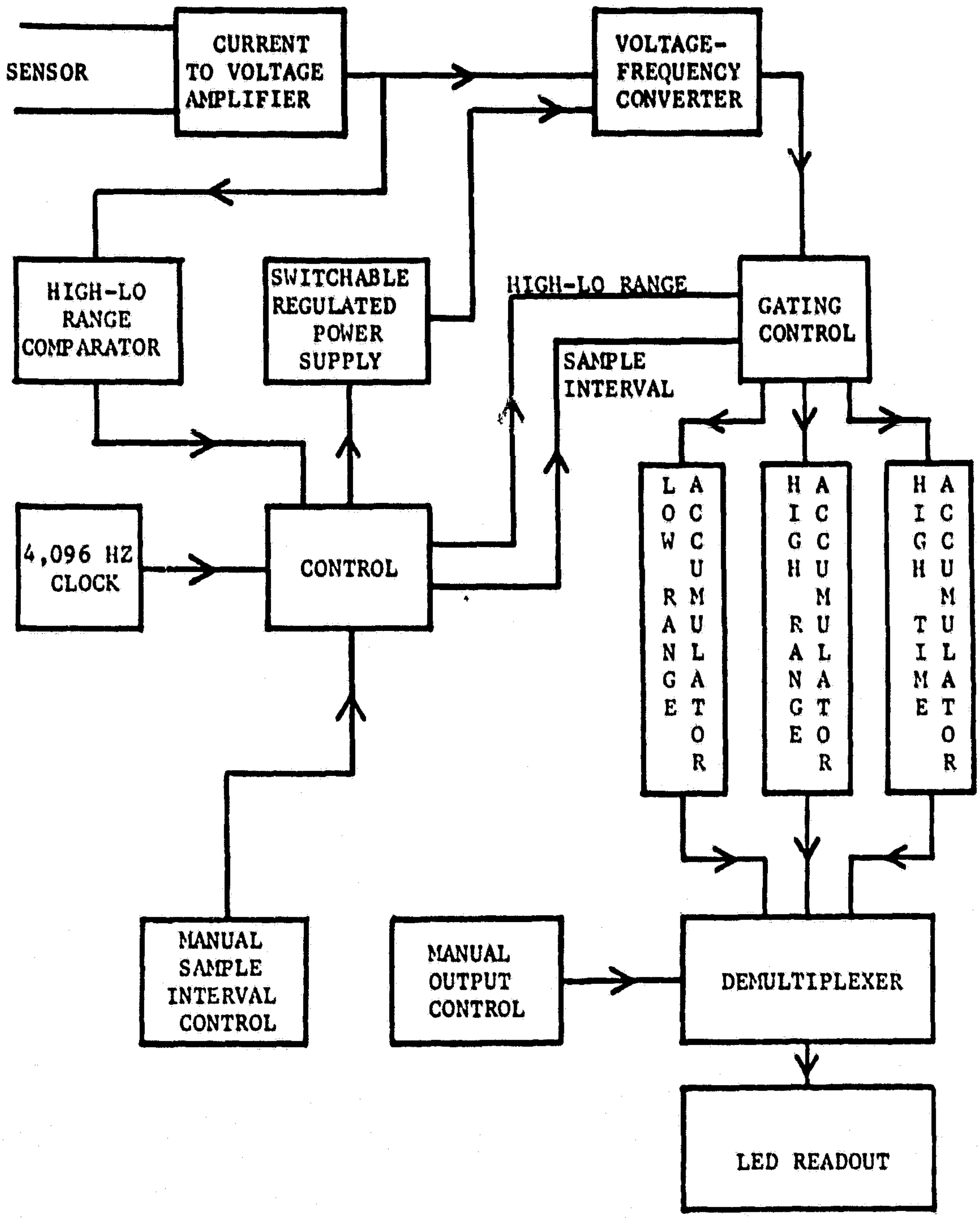

Figure 5