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WILLIAM MICHAEL LORKOVIC

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CRACK MORPHOLOGY IN CORROSION-FATIGUE

OF 2024-T4 ALUMINUM ALLOY

APPROVED BY

Raymond D. Daniels

Daniel D. Christian

F. M. Townsend

R Craig Jerner

C. M. Sliepcevich

DISSERTATION COMMITTEE

ABSTRACT

The purpose of this research was to investigate the crack morphology of an aluminum alloy under fatigue and corrosion-fatigue conditions and to study the effect of experimental variables on the cracking characteristics of the alloy.

An aluminum alloy, 2024-T4, was tested in fatigue and corrosion-fatigue, in both plate flexure and rotating bending. Other variables were stress level, speed of testing, and time under test.

At higher stress levels, the rotating bending fatigue tests revealed a large secondary cracking density. The plate flexure fatigue tests resulted in a much lower secondary crack density. The stressing conditions of the specimen appear to be an important variable in fatigue testing.

The secondary crack density in the plate flexure corrosion-fatigue tests exhibits a minimum at an intermediate stress used. This crack density increased as the test stress was either raised or lowered from the intermediate value. The stress versus time of test relationship controled the type of cracking which occurred. High stress-short time tests resulted in a maximum of transgranular cracking, both the "dry" and corrosion-fatigue types. At a lower stress

and for longer testing times, intergranular damage predominated. No major differences were noted in the cracking characteristics due to the two testing speeds used.

The secondary cracking in the rotating bending corrosion-fatigue samples was usually associated with extensive pitting and intergranular attack. However, it was seen that at a high stress, it was possible for a corrosion-fatigue specimen to exhibit much secondary cracking, yet not contain any pitting or intergranular corrosion. The stress level used in this instance was lower than that which would cause multiple cracking in fatigue.

Where visible on the fracture surface of the rotating bending specimens, fatigue and corrosion-fatigue striations followed no discernible orientation.

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CRACK MORPHOLOGY IN CORROSION-FATIGUE

CHAPTER I

INTRODUCTION

This study was undertaken to provide a better understanding of the corrosion-fatigue process, one of the most complex combinations of stress and environment to which a material can be subjected. Corrosion-fatigue, simply stated, is the concurrent action on a material of a corrosive environment and an alternating stress cycle, while fatigue is the action on a material of the application of an alternating stress in the absence of a corrosive environment. In practice, the term fatigue is used to denote the effects of cyclic stress under atmospheric conditions and corrosion-fatigue describes fatigue under more deleterious environments.

Some confusion exists in the terminology of fatigue and corrosion-fatigue testing, not only in the possible interchange of the terms, but also in the misuse of the term stress corrosion. Stress corrosion results from the concurrent action of a static stress and a corrosive environment where the attack is concentrated along a limited number of paths running roughly at right angles to the direction of the tensile stress. Only certain alloys, under certain environmental conditions, are susceptible to stress corrosion. This distinction should be understood, since all alloys, given only that they will corrode in the environment employed, suffer damage in corrosion-fatigue.

The research and literature of both corrosion and fatigue are so extensive that the sheer magnitude of published findings all but boggles the mind. As an example, a bibliography on fatigue compiled by Mann (1) which covers only the years up to 1938, contains over 2100 entries. Yet the real interest in fatigue has greatly accelerated in the twenty years since the end of the second world war. The number of papers, articles, books, etc., that have been published on the subject of corrosion would be almost incalculable. Yet, even with this extensive background in both fatigue and corrosion, the literature on corrosion-fatigue is comparatively sparse. While many reasons might be given for this lack of information the major one is certainly the sheer complexity of the problem.

On a theoretical basis, corrosion phenomena are reasonably well understood. In most cases where the corrosive environment and a materials behavior are known, there are methods available to control the corrosion or reduce it to a manageable amount. On the other hand, there is to this day no really mechanistic theory of fatigue, let alone corrosion-fatigue. Most textbook discussions, relying mainly on dislocation theories, are very qualitative. Although the admittedly complex fatigue phenomenon does not seem to deter the majority of researchers, the addition of one more variable, the corrosive atmosphere, drastically reduces the numbers of workers in the field. These investigators working on the theory of fatigue probably feel that once the "simpler" fatigue phenomenon is understood, an additional variable can be tackled. However, as will be seen later, the addition of a corrosive atmosphere results in a more complex situation than simply the addition of one more variable.

One ironic aspect of fatigue research must be mentioned. Most so-called fatigue is in reality corrosion-fatigue, since, as noted above, it occurs in a mildly corrosive environment--the atmosphere. Oxygen and water vapor cannot be completely ignored when conducting fatigue tests. The fatigue lives of most metals increase when tested in a vacuum.

The first American work on the subject of corrosion-fatigue was not planned initially as an investigation into corrosion-fatigue, but as an examination of the effects of temperature on the shape of the curve connecting the range of stress and number of cycles to fracture of specimens fatigued in air. McAdam (2) investigated the effects of altering the temperature of the test-piece by various methods, which included the use of various cyclic speeds, cooling the specimen by a water stream, and altering the heat transfer to the specimen by changes in its shape. When, however, the experiments on the water-cooled specimens were extended to include lower stress ranges and correspondingly greater endurances, McAdam encountered abnormal results which indicated that a chemical as well as a thermal action of the water stream was involved, and that this chemical action had "unexpected influence on the fatigue-resisting properties". To this concurrent action, he applied a new term "corrosion-fatigue". He published the first of a large body of papers on this subject in 1926. In his very systematic and comprehensive investigations the corrosion-fatigue properties of a large range of metals and alloys were studied. McAdam also studied the general effects of composition, heat-treatment, and the inter-relationship of the factors, stress, time, and the number of cycles on damage.

Factors Affecting Fatigue and Corrosion-Fatigue

There are many factors which affect the corrosion and fatigue behavior, and therefore the corrosion-fatigue behavior of a material. The more important ones that have been studied include the following:

Cast-vs-Wrought Products

The material used in this investigation was extruded 2024-T4 aluminum alloy, a wrought product. Templin, Howell, and Lyst (3) have shown that, in general, the fatigue strengths of wrought aluminum alloy products, using specimens with smooth surfaces in rotating-beam tests, are appreciably higher than the fatigue strengths of the commercial or permanent-mold cast alloys. On the other hand, the fatigue behavior when sharp notch type specimens were used, showed no significant differences between the wrought and cast aluminum alloys.

This difference in the fatigue strengths between wrought and cast materials in the smooth specimen tests is to be expected. The undoubted difference in the surface finish, the worst probably that of sand castings, would be a major factor in the fatigue lives of the test specimens. On the other hand, the lack of any significant difference between the notch values points up the importance of specimen geometry and surface condition on the fatigue lives of aluminum alloys.

It was shown that most differences between the fatigue behavior of wrought and cast products could be eliminated if the casting could be done under carefully controlled conditions to eliminate inclusions and porosity. If large commercial ingots or castings could be made equal in quality to laboratory ingots, no significant improvement in fatigue values would be expected by working.

Grain Size, Direction, Inclusions

Templin (4) points out that there are persuasive arguments in the literature, as for instance those of Teed (5), that large grain size specimens have a lower fatigue life than do smaller grained specimens. Thompson (6) makes the reasonable speculation that this reflects the difficulty of propagating a crack across a grain boundary.

There is much data on aluminum alloys, however, that indicates that grain size, as such, probably has no significant effect on the fatigue strength of the alloys. The alloys tested by Templin had grain sizes which varied from very fine ($170{,}000/mm^3$) to very large ($0.003/mm^3$). These specimens tested to almost identical fatigue values. It was concluded that something other than grain size was the probable cause of differences in fatigue strengths originally attributed to grain size simply because a difference in grain size was found.

An even more dramatic finding by Templin, Howell and Hartmann (7) was that grain direction, as such, in wrought aluminum alloys had no significant effect on the fatigue properties of the alloys. In some specific instances, the presence of oriented constituents, inclusions, or highly elongated and unhealed porosity was found to effect both the fatigue properties and the tensile properties of the material. In the absence of these conditions, but with pronounced grain flow due to working, the fatigue properties were practically the same in all directions.

Temperature

Frith (8) demonstrated that the most general effect of temperature on non-ferrous metals at a given stress is the decrease in fatigue life with increasing temperature. Low carbon steels are unusual in this respect. According to Levy and Sinclair (9) their fatigue life increases, reaching a maximum at approximately 230°C, above which the normal temperature dependence is resumed.

Most low temperature fatigue data are available for copper, studied by DeCammon and Rosenberg (10) and Forrest (11). The endurance limit of copper increases by a factor of three in going from room temperature to -269°C. There is not much data on the temperature dependence of fatigue strength of aluminum alloys, but the data available indicate that aluminum follows the general temperature dependence trend indicated above. The fatigue strengths of most commercial aluminum alloys tend to approach a common value at a temperature of about 600°F, the temperature at which the low temperature strengthening effects are lost.

Surface Condition, Stress Raisers

There have been theories of fatigue which presume that the fatigue crack can initiate beneath the surface of a material. There is no evidence to support this and much that suggests that, in pure metals at least, all cracks originate in surface intrusions formed by slip. Atkinson (12), Franks and Thomas (13) and Grosskreutz and Rollins (14), using both X-ray and neutron scattering techniques, tried to observe the initiation of crack nuclei in the interior of metals undergoing fatigue. Less than one per cent of the observed scattering could be interpreted as cavity scattering.

Because of the importance of the surface of the fatigue specimen, its preliminary condition and treatment during testing play a major role in both the fatigue and corrosion-fatigue results. Fig. 1, from unpublished work

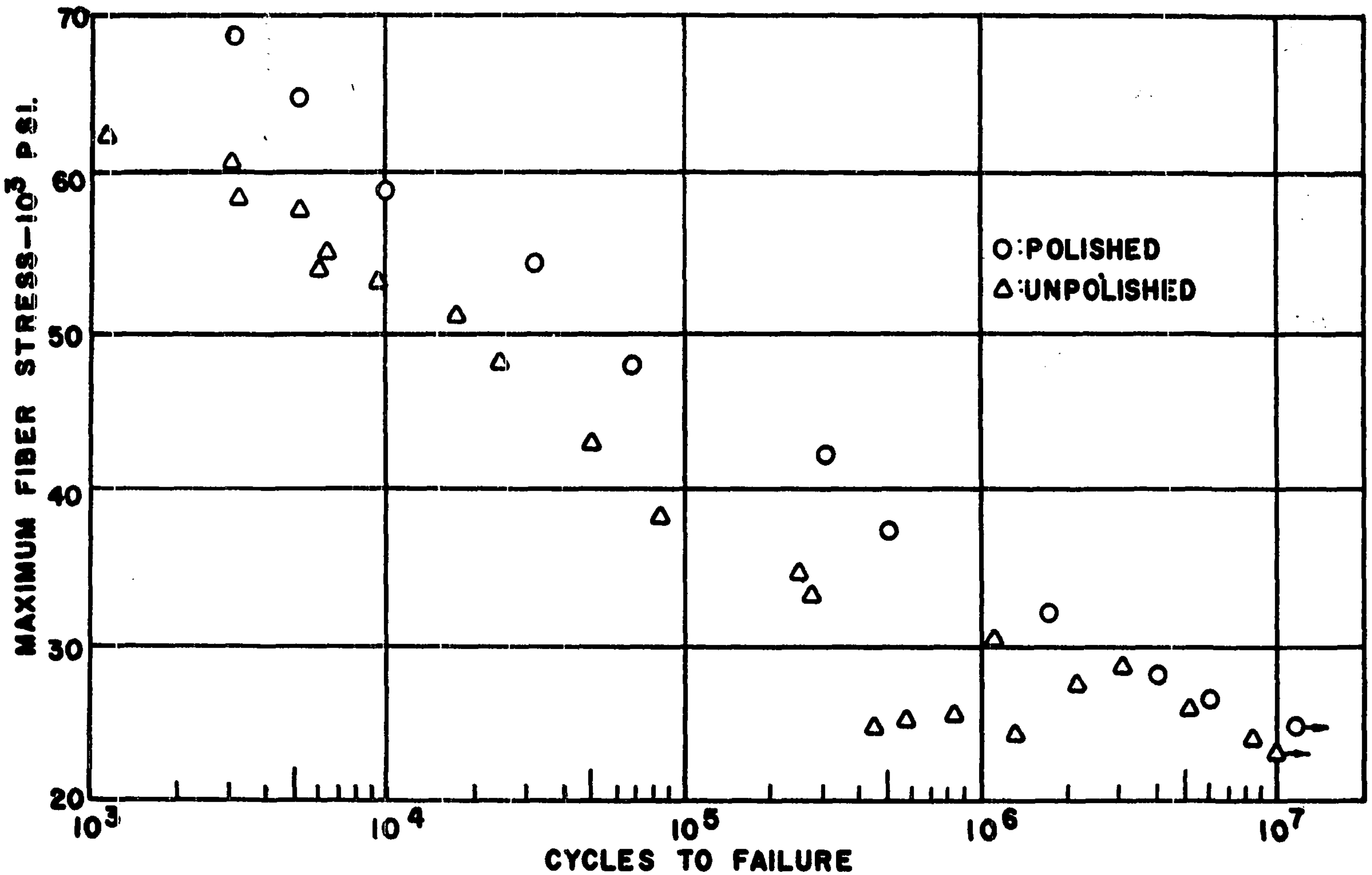


Figure 1. Fatigue Data on Polished and Unpolished Samples, 2024-T4 Aluminum Alloy Rotating Bending Test, 6,000 RPM.

done at the University of Oklahoma, indicates the difference in fatigue strengths of as-machined and as-polished specimens of 2024-T4 aluminum alloy. These data are shown graphically with the maximum fiber stress (S) the ordinate and the cycles to failure (N) the abscissa. This is the most common form for the presentation of fatigue data. The machining marks on the specimens were perpendicular to the applied stress and were, in effect, stress raisers. The polished specimens contained fine scratches left from the polishing operation, but these scratches were in all cases parallel to the applied stress. The object of the polishing procedure is to eliminate the original machining marks. Except for the lower stress levels, polishing increased the permissible stress at any given life by approximately 10,000 psi.

Stress raisers, or "notches", and their effect on the fatigue lives of materials has been extensively studied. The presence of stress raisers in the form of grooves, holes, slag inclusions, machining marks, accidental dents or scratches, etc., will promote the initiation of a fatigue crack at these points. Most stress raisers are not introduced intentionally, but accumulate during service. Since little can be done in a practical way to eliminate the stress raiser, and since some are built into a member in the form of holes, it is desirable to know what effect these might have on the fatigue life of the member. Therefore, much fatigue testing is done on both smooth and notched samples and a fatigue strength reduction factor (K_f), taken as the ratio of the two nominal stresses which give the same fatigue life, is determined. Some argue, persuasively, that this test is as much a testing of a machinist's skill in making a notch of a specific root radius as it is a test of the material, but the test does at least provide a basis for comparing laboratory results with projected engineering applications. An additional, and experimentally important use of the notched test, is in predetermining where the fatigue cracks will start so that their progress can be detected and their growth followed.

The scatter of values in the standard S-N fatigue curve is much less for notched specimens than for the smooth specimens. With a notch, the probability of crack initiation in a definite place is increased. On the other hand, results from Templin (4) for two aluminum alloys showed poor agreement between theoretical elastic stress concentration factors calculated for the notches and the actual strength reduction factors obtained.

Surprisingly, Frost and Phillips (15) have shown that non-propagating cracks can be initiated at the root of a notch, provided that the root radius is small enough. If one calculates the "stress concentration factor", K_t, defined as the theoretical stress at the notch divided by the nominal stress, it was found that there is a critical value, above which non-propagating cracks are formed. These authors did not observe non-propagating cracks in un-notched specimens.

Size Effect

It is a well known, but usually ignored fact, that the mechanical properties of a metal, as determined by tensile tests, vary with the tensile specimen size. This factor has not been extensively studied in fatigue. Templin (4) states that for a few aluminum alloys which were tested, there was no size effect throughout the range investigated. While the specimens varied in diameter from about 1/8 in. to 4 inches, the data were not entirely consistent and the author indicated the conclusion is tentative until more alloys in more conditions could be tested.

Strain Hardening and Heat Treatment

According to the Metals Handbook (16), steel, when quenched to 100% martinsite and then tempered, increases in fatigue limit with increasing hardness up to about 35 Rockwell C in a reasonably linear manner. While steels of increasing hardness, treated in a like manner, continue to increase in fatigue limit, the scatter band of the data similarly increases. Up to 35 Rockwell C the scatter band is approximately 18,000 psi. From this hardness up to 55 Rockwell C the band increases to approximately 45,000 psi, although most of the values can still be placed in the lesser 18,000 psi band.

For aluminum alloys, cold working increases the yield and tensile strengths with a less than proportional increase in their smooth specimen fatigue strength. In general, the notch fatigue strength is not affected by cold working.

Almost all of the heat-treatable wrought aluminum alloys, when heat treated from either the annealed or the cold-worked condition, show an increase in both the smooth and notch specimen rotating-beam fatigue strengths of about 50 per cent over those of the annealed material. Further hardening by a precipitation heat treatment, for those alloys so designed, causes no increase in the fatigue strengths. Cold work, after heat treatment of the high strength wrought alloys, results in little change in the fatigue strengths.

The endurance limits of some of the aluminum alloys in the fully annealed condition are equal to or greater than their yield strengths. This interesting fact makes the determination of these specific fatigue values difficult, if not impossible, since stresses applied at or above the endurance limit plastically deform and cold work the metal with the result that the metal is no longer in the annealed condition.

Both cold working and heat treatment can result in residual stresses in materials. Depending on their orientation with respect to the applied stresses the residual stresses can be harmful or beneficial. Residual tensile stresses, when parallel to the applied stresses, will help open an incipient crack and will enhance crack propagation. Residual compressive stresses tend to keep the crack from propagating and hence, increase the fatigue life. Shear stresses appear to be operative only in helping to initiate the crack.

Gough (17) was the first to demonstrate that if some metals are pre-stressed for a large number of cycles below their fatigue limit, their fatigue life at elevated stress was much increased. This phenomena is called coaxing. While Sinclair (18) found that aluminum failed to respond to pre-stressing, it is now felt likely that this coaxing effect is present to some extent in all metals.

Environment

Any corrosive environment in contact with the surface of a metal will materially effect its fatigue life. Even normal laboratory atmospheres are mildly corrosive to most metals. In their study of this "mildly" corrosive atmosphere, Wadsworth and Hutchings (19) found that the fatigue life of copper could be increased by a factor of 20 over its normal value in air if the sample was tested in a vacuum. The increase was not so large for aluminum, 5 to 1, and was non-existent for gold. This strongly suggests that corrosive action at the surface in air was responsible for these results.

Another result of this research was that the intermediate step of removing the sample from the vacuum and exposing it to air for examination did not affect the vacuum fatigue life. From this it is inferred that atmospheric effects are operative at the metal surface only during cyclic stress. Moreover, it was found that other atmospheres

(O_2, H_2O vapor) affected various metals differently, which again suggests a chemical action or attack at the surface. Finally, it was observed that the formation of fatigue cracks at the surface was unaffected by the presence or absence of an atmosphere, but that the development and propagation of the crack depended strongly on the partial pressure of various gases.

Some early work by Gough (20) showed that the fatigue results for copper and brass in damp purified air were almost identical to those in ordinary air. In dry purified air, the fatigue limit for copper was near to that in a partial vacuum, and for brass it was above that in ordinary air, though not as high as in a partial vacuum. It was concluded that the acid and alkaline impurities in the atmosphere (CO_2, SO_2, HN_3, etc.) play little or no part in the action which results in a reduced fatigue limit in ordinary air, but that oxygen and water vapor play a vital part. It was concluded that "the effect of atmospheric corrosion-fatigue is due to the catalytic agency of water in the presence of oxygen."

Lehmann (21) reported that for steel, there was little reduction in strength when the specimens were tested at 96°C in distilled water, a sodium chloride solution, or a sodium nitrate solution, although there was some reduction in an ammonium chloride solution. These tests were carried out with a tube enclosing the specimens, the aqueous solutions entirely filling the space between the specimen and the tube. It is probable that the negative results were due to the restricted access of oxygen and the reduced solubility of oxygen at 96°C.

This latter point is illustrated in the work of Binnie (22) who showed that a sodium chloride solution dripping through air onto the samples produced very destructive results. When the solution dripped through commercial hydrogen, slightly higher values were obtained, and when purer hydrogen was used, there was still further improvement. As the electrochemical mechanism of corrosion came to be more fully understood, it was recognized that in conditions where the cathodic reaction is reduction of dissolved oxygen, the supply of oxygen to the specimen surface will be a controlling factor in the rate of corrosion. This explains the importance of oxygen in many cases of corrosion-fatigue. Nevertheless, it is possible to conceive of corrosion-fatigue occurring in the absence of oxygen in environments where the cathodic reaction is the evolution of hydrogen. Evans (23) showed this to occur in the corrosion-fatigue of steel in acid solutions.

Ferrous metals, when tested in air, exhibit an endurance limit, i.e., there is a stress below which failure will not occur in a reasonable time. When they, or any material having an endurance limit, are tested in corrosion-fatigue, no endurance limit can be found. The S-N curve continues to decrease as the cycles to failure are increased. For the engineer, this is the single, most important fact about corrosion-fatigue. Since aluminum alloys do not have an endurance limit, when they are tested under corrosion-fatigue conditions the basic shape of the S-N curve is not changed. Its position is merely shifted to shorter times and lower stresses.

If the stress applied to a material is static rather than dynamic, the application of a corrosive atmosphere results in a possible stress corrosion situation. Meikle (24) showed, on tests conducted on British aluminum alloys similar to 2024-T4, that these alloys had very little tendency to stress corrode. Actually the alloy can be considered immune under most normal conditions. The test consisted of suspending the specimens in a room (T - 20°C ± 1°C, relative humidity 80% ± 3%) with tensile stress applied. The specimens were sprayed three times a day with sea water.

Testing Speed

While by no means exhausting the total number of variables in fatigue testing, the preceding discussion does include all those of importance, save one. The speed of the application of the cyclic load is usually ignored in fatigue testing. Since the testing procedure may involve the application of many millions of cycles, the philosophy usually followed is to test as fast as is reasonably possible with the test equipment used. This may be justified in fatigue testing, but cannot be tolerated in corrosion-fatigue testing if meaningful results are to be obtained. The rate of stress cycle application is a major variable and must be treated as such. Fig. 2 shows this effect of cycling rate on an aluminum alloy tested on a rotating beam machine in a corrosive environment. These data taken from unpublished work at the University of Oklahoma show clearly that corrosion-fatigue life is reduced as the speed of testing is decreased.

In corrosion-fatigue, two factors act concurrently; the application of an alternating stress is coupled with the action of a corrosive atmosphere. In simple fatigue testing, there seems to be no reason to suspect that the life of the material under test would have any dependence on the rate of application of the stress. If, however, corrosion processes are occurring at the surface of the material, a time dependence, and therefore, a sensitivity to the rate of application of the stress, results. A mildly corrosive atmosphere such as air will affect the results of fatigue tests only if they are conducted at comparatively slow speeds. An increase in the test speed, and therefore, a shortening of the tests, masks or completely nullifies the effect of a mildly corrosive atmosphere. This is what has occurred in most so-called fatigue tests where the results have been obtained at a high speed. If this material is then placed in service where the rate of application of the stress is much slower, which is generally the case, the fatigue life could be and undoubtedly is lowered. In spite of these observations, in very few fatigue studies reported in the literature is the speed of the test mentioned. Only a handful of careful or knowledgeable authors add this information. It should be apparent

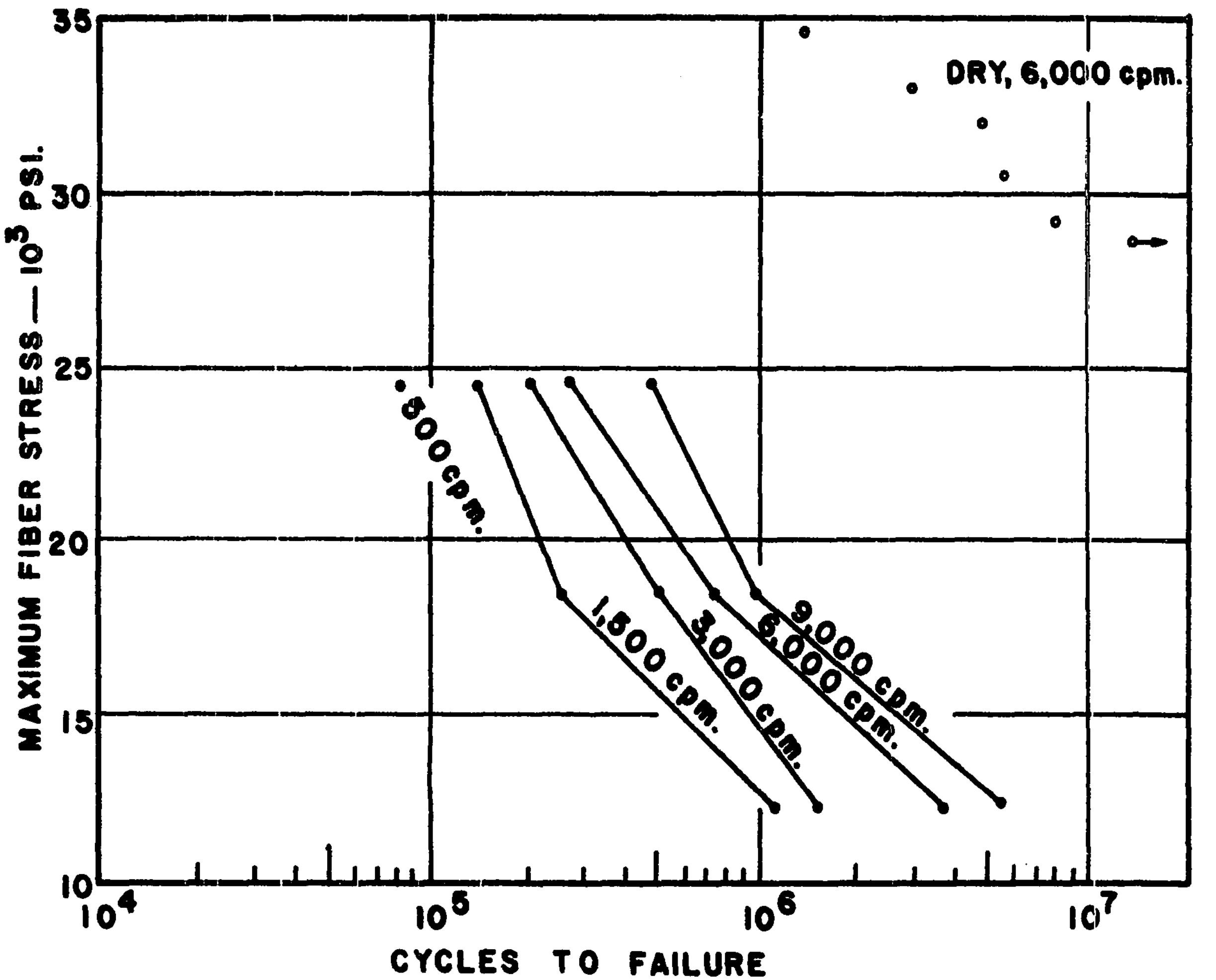


Figure 2. Influence of Testing Speed on Corrosion-Fatigue Properties of 2024-T4 Aluminum Alloy, Rotating Bending Test, 3% NaCl Solution

from the foregoing that corrosion-fatigue values published without stipulating the rate of testing would be almost useless and that even fatigue values without this information would be less than completely useful.

On a test of a British aluminum alloy (DTD 687), Harris (25) reported that at a fatigue life of 10^6 cycles, a specimen tested at 10 cycles per second could support a load of approximately 13,500 psi. If the speed of testing was increased to 1000 cycles per second the load was 22,000 psi. Put differently, these same data show that a specimen could support 20,000 psi for slightly over 10^5 cycles at 10 cycles per second but more than 10^6 cycles if the speed of the test was 1000 cycles per second. These tests were conducted in air.

The complexity of corrosion-fatigue testing has already been suggested as a possible deterrent to the research in this field. Another problem encountered in the corrosion-fatigue literature is a simple refusal, or even perhaps an inability of researchers to come to grips with this subject and, in effect, call a spade a spade. This seems to be the reason why many anomalies and much fuzzy writing exists in the corrosion-fatigue literature, and why one must take care not only to determine what an author has claimed to have done experimentally, but, if possible, what he actually has done.

An example of this confusion is a report by Harmsworth (26). In this work samples were either corroded in a salt cabinet or had small holes drilled into them to simulate the salt pitting, and then they were fatigued in

R. R. Moore type machines. The author then attempted to correlate the fatigue lives of the artificially pitted specimens with those pitted in the salt spray. He states: "The above method could, of course, be applied only to service conditions where the corrosion precedes the application of load. Neither this or any other existing method of analysis is reliable enough to use at present (1961) to determine the fatigue life of a corroded structural member that has been subjected to previous fatigue loading of various degrees during its life cycle." This is all quite true, but the assumption that many service parts lie dormant while corroding and then are suddenly subjected to fatigue loading is a very restricted condition. A more important point is that the author implies that he is conducting fatigue tests on the material rather than corrosion-fatigue tests. He refers to them as fatigue tests although the term corrosion fatigue (without the hyphen, implying two separate actions) is used in the report. The author also states that the samples were not out of the salt spray more than 24 hours before "fatigue" testing. By this statement the author admits that the time the specimens spend lying on a table is important. However, the report does not make clear that the possible continuing action of any residual salt could adversely effect the "fatigue" values obtained. Reports of this type are common in the literature.

Observations on Fatigue

Research to determine the mechanisms of the fatigue process have been primarily concerned with observations of the way the initial crack is formed, how it propagates, and the possible stages into which the process can be divided.

One widely accepted division of the fatigue process is based on the dissipation of energy in the sample during testing. Haigh (27) observed that the production of heat in a sample could divide the test into three parts. The first is characterized by a heat pulse which lasts for only a few thousand cycles. Following this there is a second stage in which the heat produced rises slowly. Finally, just prior to fracture, the production of heat rises sharply. This heat production can be simply measured by recording the temperature of the sample under test. While Haigh did his original work in 1928, more recent work, by Wadsworth in 1957 (28) and Grosskreutz in 1959 (14) confirm these stages and offer additional metallographic observations. This latter work showed that the stages could be summarized as follows:

1. The first few thousand cycles during which the originally annealed sample strain hardens. The energy dissipation which is initially high falls rapidly during this period. Slip bands begin to form.

2. A long period (several million cycles) during which the energy dissipation increases slowly and the slip bands intensify. Polygonization of the metal occurs during the first portion of this stage.

3. A fairly short final period (approximately 10^5 cycles) during which a microscopic crack is visible and propagating. The energy dissipation increases rapidly during this stage which finally ends in rupture.

These observations are applicable only to pure metals and stable alloys. However, even here there is good evidence to show that energy dissipation is not directly related to fatigue crack formation or even to the fatigue life itself. Thompson and Wadsworth (29) observed that energy dissipation was a bulk phenomenon and was not affected by removing surface material or by performing the fatigue test in nitrogen, both of which increased the fatigue life. Further, a partially fatigued sample can be returned to its original energy state by a high temperature anneal, without affecting the fatigue life at all.

More recently, Thompson (6) and Bennett (30) have suggested that a better division into stages can be made in terms of the fatigue crack itself. The problem is treated in terms of (a) a period of crack formation and (b) a period of crack propagation.

The first observations of surface slip markings produced by cyclic stress were made in 1903 by Ewig and Humphry (31). More recent work by Kuhlmann-Wilsdorf, Van der Merwe and Wilsdorf (32), using the electron microscope, offers a good picture of these surface markings. A few slip lines are observed to appear during the first few thousand cycles of stress. As the test proceeds, new slip lines form beside the old ones forming what are known as "slip bands". Between the bands there are large areas in which no slip is observable. After about the first ten per cent of the fatigue life has elapsed, no new slip planes appear to be generated, but the existing slip bands continue to grow more intense, that is, the surface irregularity becomes greater.

In addition to this slip, another structural change which occurs during fatigue is the formation of misoriented subgrains. Grosskreutz (14) found that the degree of misorientation depended on the magnitude of the stress, but most of it was less than one degree. It is interesting that the great majority of the misorientation occurred within the first ten per cent of the fatigue life as does the production of new slip lines.

Slip lines have been shown to be intimately connected with the initial crack formation and propagation. Thompson, et al. (33), using polycrystalline samples, observed slip markings by periodically removing the sample from the fatigue machine, subjecting it to a light electropolish and examining the surface under the microscope. The usual slip bands appeared early in the test and became more numerous and intense as the stressing proceeded. The light electropolish seemed to remove the surface roughness associated with the slip bands. This normally made the bands invisible by reflected light except for a few which were labeled "persistent" bands. The cracks which eventually led to failure were all observed to originate in one of these persistent slip bands. The first cracks appeared after about 5 per cent of the fatigue life had passed and the rest of the test was spent in propagating the crack. Usually the first such crack to cross a grain boundary developed into the final fracture. The cracks were observed to propagate along slip bands and were always perpendicular to the direction of tension.

Hunter and Fricke (34) and Smith (35), working with different metals, have reported seeing some cracks in the materials after only 1 to 5 per cent of the total fatigue life. This leads to the important conclusion that, in pure metals at least, the greater portion of the fatigue life is spent in propagating the crack, a field of research thus far largely ignored.

Interesting observations on the earliest stages of fatigue showed that at low stresses the incipient cracks first appeared on the surface as a series of dots or pits. This has been seen on both aluminum by Smith (35) and brass by Jacquet (36). A cut section perpendicular to the surface showed that the pits were the ends of parallel tubes extending into the metal for several microns. The origin of these tubes is not clear. Literal extrusion and intrusion of a metal at the surface of a fatigue sample has been observed by Cottrell and Hull (37). This phenomenon always occurs in slip bands and has been observed in a variety of pure metals and alloys.

As previously mentioned, many attempts have also been made to observe the initiation of crack nuclei in the interior of metals undergoing fatigue. The results cited by Atkinson (12), by Franks and Thomas (13), and by Grosskreutz and Rollins (14), using diffraction scattering techniques, showed that less than one per cent of the observed scattering could be interpreted as internal cavity scattering. Thus, it appears fairly certain that fatigue cracks do not have as their origin clustered vacancies accumulating in the interior of a metal. The experimental evidence strongly favors the initiation of a fatigue crack at or near the surface of a sample, probably at a "notch" which may have been created in a variety of ways depending on the purity and constitution of the metal.

The importance of the surface is emphasized by a number of experiments which have shown that the fatigue life of a sample can be prolonged indefinitely by polishing off the surface at regular intervals during the test. It can be argued that even if the surface of a fatigue sample is crystallographically perfect and free of all machining marks and polishing or etching marks, a crack would eventually form at an intrusion or pit in the fine slip bands. Thus any material, if it is crystalline, is subject to fatigue.

The electrochemical concept of corrosion-fatigue is mainly due to Evans (38). Without applied stress, there will usually be a tendency for the formation of protective films and the stifling of attack by insoluble corrosion products. When cyclic stresses are imposed, the induced cyclic strains "tend to rupture, or render more permeable, the protective film, and to dislodge or remove the other products of corrosion." Pitting begins at the local points of breakdown and, owing to the local stress concentration, one of these pits will soon tend to develop into a sharp-pointed crevice. Evans writes, with a clarity rare in the literature, "The probability of attack will be maximal at the bottom of the cavity, since at that point the strongest forces will be available to break any protective film which may be formed, or to distort the lattice and make the metal less stable. Thus, whether the corrosive agent is one capable of forming films or not, the cavity will prolong itself in this direction in preference to any other and will tend to become pointed; the corrosion proceeding at the pointed end of the crack will exert a protective action on the region around and automatically reduce the chance of corrosion at the sides; this will mitigate against serious widening. Thus, when once a cavity has become narrow and pointed, it will tend to remain narrow and to penetrate progressively into the metal". The rate of penetration will slow down as the crack deepens, owing to the increased resistance between the tip of the crack and its mouth, and other pits will tend to develop into cracks and catch up with the initial one. A whole series of cracks will thus develop, and as they progress inward, the mechanism will become less electrochemical and more mechanical. Eventually, one crack will become so far advanced, and the stress concentration so great, that the fatigue limit of the material will be exceeded and failure will be completed by fatigue.

Theories of Fatigue

It should be evident that any theory of fatigue which must account for all of the varied aspects of the phenomenon will not be a simple one. This point of view has certainly discouraged quantitative calculations. Almost any set of arbitrary assumptions can be used to fit any single S-N curve, since these curves are subject to so much experimental scatter. On the other hand, recent observational evidence suggests that fatigue can be reduced to manageable proportions, theoretically speaking. A division of the fatigue process into crack initiation and crack propagation seems necessary, since the same theory obviously will not fit both processes. Concentrating on crack initiation, one tries to set up a mode of crack initiation in which the time scale is a few thousand cycles. The fact that a metal can be fatigued at $4°K$ in a liquid helium atmosphere argues that basically one need not consider such things as surface corrosion, diffusion of vacancies, or surface adsorption of gas molecules in the theory, although these factors will certainly influence fatigue if operative. Stated as simply as possible, a crack is formed purely as a result of the movement of dislocations in a crystalline lattice bounded by free surfaces.

Dislocation Models

Two screw dislocations whose lines of dislocations are at right angles and which travel so as to intersect each other, will produce "jogs" in their dislocation lines, according to Read (39). Depending on the direction of movement of the screw, the climbing of the edge segment, or jog, will result in either a row of interstitial atoms or vacancies left behind. Any accumulation of the above vacancies into clusters in the slip planes could be a potential crack. This is an attractive hypothesis. However, the experiments mentioned before to detect cavities in the interior of a metal following cold work have all been negative. Also, the fact that fatigue occurs at extremely low temperatures where vacancy diffusion is difficult makes the hypothesis untenable. Nonetheless, the mechanism of vacancy production is an important one and undoubtedly goes on during fatigue.

Dislocations may "pile up" near a grain boundary or other impediments to their freedom of movement. The tensile stress near such a pile up might be strong enough to cause rupture and produce a crack. Fujita (40) suggests that two such groups of dislocations on neighboring glide planes would produce a crack approximately 10 Angstroms wide between them.

Attempts have been made to devise a dislocation mechanism which would produce the extrusions and intrusions observed on the surface of fatigue samples. Cottrell and Hull (37) suggest that the interaction of two Frank-Read sources on different slip systems would produce an intrusion on one and an extrusion on the other. Mott (41) gives a model based on a mechanism for the formation of a cavity and on cross-slip for the growth of the cavity which results in the extrusion of metal at the surface. The model is independent of both temperature and environment. It suffers, unfortunately, from two major criticisms: (1) it does not explain intrusions and (2) it requires that a cavity exist below an extrusion, which has not been observed.

The above summary gives some idea of the state of the theory of fatigue crack initiation. It consists mostly of hypotheses, very qualitative in nature, which attempt to explain the observed facts. In spite of the thousands of papers published on the subject, it is clear that the definitive research in this field lies in the future.

Statistical Theories

The inability to develop a quantitative theory of fatigue based on a specific model plus the seeming statistical nature of fatigue failure has led many researchers to propose theories based on statistical models. Statistical theories are not substitutes for, nor competitors of the theories discussed above which are based on the actual mechanism of fatigue. Rather, they are attempts to fit the data (the S-N curve) using a minimum number of assumptions concerning the basic mechanism. They contain certain "adjustable parameters" which must be determined by experiment for each metal to which the theory is applied. Finally, their reason for being is that they could be used to predict fatigue performance for stress loads and endurances which are beyond practical experimental reach.

Most of the statistical work has been in the determination of fatigue life under varying stress amplitude. While not a purely fundamental problem it does have large practical usage, for few parts are subjected to fatigue stresses at a constant stress amplitude. Therefore, the question naturally arises as to how best to apply laboratory test results giving fatigue life at a constant stress amplitude to such a problem. Experiments have shown that cumulative damage at different stress levels is not linear, and this has led to elaborate fatigue tests using "programmed loading" covering a wide range of stress. The statistical approach to fatigue is particularly applicable to this problem.

Miner (42), Newmark (43) and Corten and Dolan (44) have all presented statistical theories. Thus far, the most successful seems to be that due to Freudenthal (45) and Freudenthal and Gumbel (46). In the latter theory, rather than thinking of the S-N curves with their scatter of experimental points, one should think in terms of the probability of survival (or failure) after N cycles of stress S. Experimentally (and theoretically) the proper data to determine are the probability of survival after N cycles at a constant stress S, or the probability of survival at a stress S for a constant number of cycles N. S-N curves can then be plotted from the data, but now they are S-N curves for a given probability of survival.

The statistical theory itself is based on a probability calculation of the cumulative disruption of atomic bonds. The adjustable parameters, to be determined by experiment, are the distribution of atomic bond strengths, the distribution of the stresses on the bonds induced by the applied stress and the number of broken bonds needed to produce fracture. Very good agreement with experiment has been obtained and useful extrapolations have been made for predicting survival at high confidence levels impractical to obtain by direct fatigue testing procedures. In the sense that this theory does provide this possibility, it is the best theory of fatigue that has so far been presented.

CHAPTER II

EXPERIMENTAL OBJECTIVES AND METHODS

This investigation was primarily concerned with a detailed study of the crack morphology of an aluminum alloy subjected to the concurrent action of alternating stresses and corrosive environments. The objective of this study was to evaluate the interrelationships between stress and environment by determining the morphology of fatigue cracks and the rate at which these cracks form and grow. The reference environment was normal laboratory air which may be considered to have only a mildly corrosive effect. This environment was compared to a specific corrosive medium, an aqueous solution of sodium chloride.

In addition to the differing atmospheres, several other variables which influence crack behavior were examined. These were stress level, stress cycle frequency, and the geometry and manner of loading the test sample. Two sample configurations and methods of load application were employed. These were the rotating bending test and the plate flexure test. In the rotating bending test, the sample is cylindrical and is end loaded as a cantilever beam while rotating. This is a fixed load test. In the plate flexure test the sample is a tapered plate which is subjected to reversed cantilever bending of fixed deflection. Each of these tests has its advantages and disadvantages for fatigue testing. One is designed for plate material and the other for rod material which may have very different fatigue characteristics for the same alloy. Since the objective was to evaluate the combined effects of stress state and environment, the results obtained for each of the tests are considered separately and conclusions and interpretations are correlated with the differences in test materials and conditions.

Rotating Beam Testing

In the rotating beam fatigue test program the mechanical properties of the bar stock used were determined to be sure that they conformed to the strength specifications applicable to the alloy. Next, basic fatigue S-N curves were determined for the alloy under two atmospheric conditions. Three fatigue lives were then chosen for each condition upon which all subsequent tests were concentrated.

Specimens were run to failure or to a specific percentage of their anticipated life at the chosen stress levels. The specimens were then tested to failure in tension to determine the residual strength after fatigue or corrosion-fatigue testing.

Where possible, after tensile testing, the cross-sectional area fractured in either fatigue or corrosion-fatigue was estimated. Both the outside surface and the fracture surface of each sample was microscopically examined. The outside surface was examined for the presence of cracks, pits or other surface flaws; while the fracture surface was examined for the presence of striations characteristic of fatigue fracture surfaces.

These data and correlations drawn therefrom are presented in succeeding chapters.

The fatigue machines used in this part of the investigation were of the R. R. Moore type. This equipment used a cylindrical sample, one end of which is held in a chuck and rotated by a variable speed motor. From the other chucked end of the sample, a weight is hung making the specimen a part of a cantilever type suspension. By this means the sample surface is subjected alternately to tension and compression stresses during each cycle of rotation. One of these units is shown in Figure 3.

Two of these machines were used during this investigation. Normally, one was used exclusively for the fatigue tests and the other for the corrosion-fatigue. At various times during the program the machines were checked for compatibility of results. These checks took the form of running fatigue tests on the machine normally used for the corrosion-fatigue and using the corrosion fixture on the machine normally used for the fatigue tests. Table I shows the results obtained in these tests. The fatigue

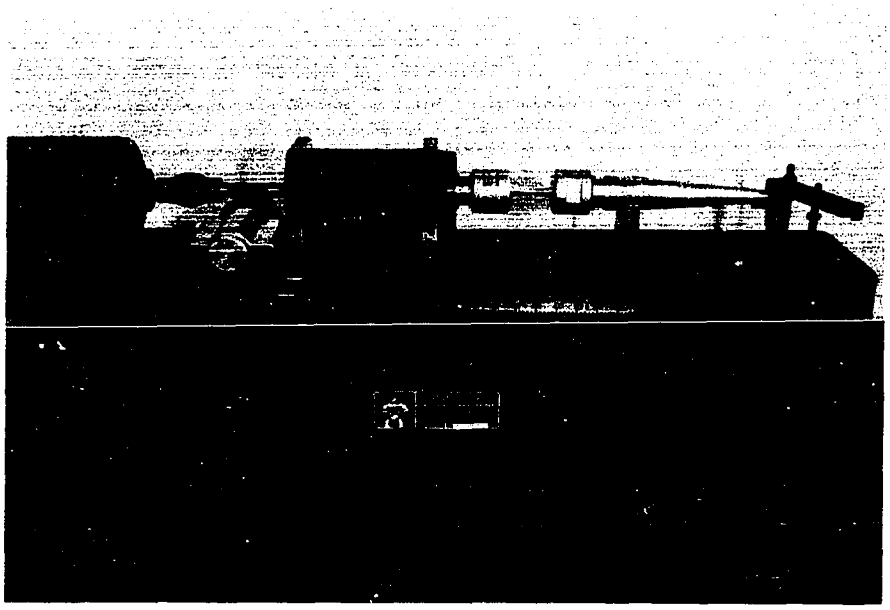


Figure 3. R.R. Moore Type Fatigue Machine
Fatigue Specimen in Place

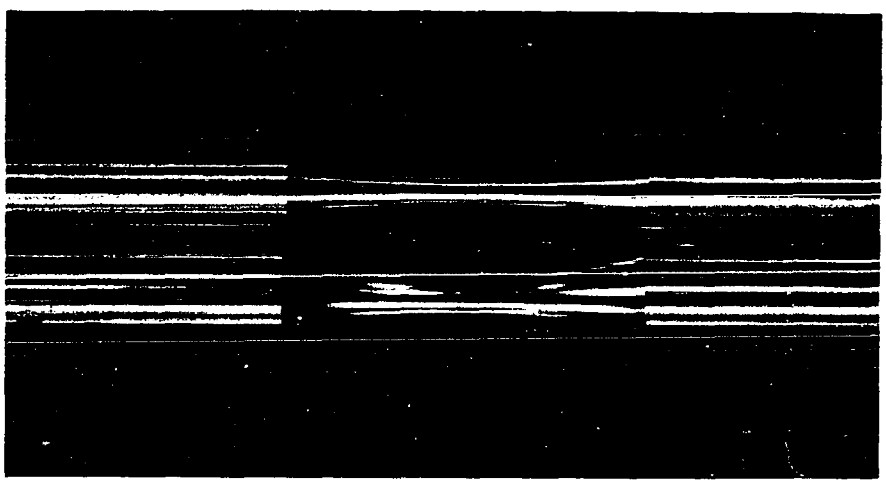


Figure 4. Rotating Beam Fatigue and Corrosion-
Fatigue Specimens. Top: As Machined
Bottom: As Polished

TABLE I

COMPARISON OF RESULTS OBTAINED ON TWO R. R. MOORE TYPE FATIGUE MACHINES

Environment and Spec. No.	Stress Psi	Cycles to Failure	Machine Used	Known Scatter Band (approx.) Ref. (4)
129 "Dry"	31,100	443,400	"Wet"	$4 \times 10^5 - 2.5 \times 10^6$
224 "Dry"	23,300	7,888,500	"Wet"	$1.7 \times 10^6 - 10^8$
512 "Wet"	15,050	898,600	"Dry"	---------------
315 "Wet"	17,000	535,600	"Dry"	---------------

results, regardless of the machine used, are within the known fatigue scatter band for this alloy. No such band exists for the corrosion-fatigue results, but the scatter here seems to be compatible with the rest of the corrosion-fatigue results.

The cylindrical specimens were machined from 2024-T4 aluminum alloy bar stock. This alloy was chosen not only because it is a well known, much used, commercial alloy, but also because a previous investigation of this alloy at the University of Oklahoma (47) provides us with much preliminary information as to its gross fatigue and corrosion-fatigue behavior. One of the specimens as-machined is shown in Figure 4. The main requirement for a fatigue sample of this type might be assumed to be a completely smooth curved test surface. However, it was found during the above mentioned investigation that reproducible results which fall within the well established fatigue scatter band of this alloy could be obtained just by a longitudinal polish with a fine polishing paper. The main requirement for assuring reproducibility and a maximum fatigue life is to remove all of the transverse machining marks, those which would be perpendicular to the applied stress. The tool used for the mechanical polish was an aluminum cylinder with a radius equal to the radius of the machined test section of the specimen. A piece of 320 grit emery paper was placed around this cylinder which was then chucked into a drill press and rotated. The specimens, held against the cylinder by hand, were slowly rotated until the original machine marks were no longer visible. Since the speed of rotation of the drill press far exceeded that of the hand, all of the remaining scratches on the specimen were longitudinal.

The specimens polished in the above manner give acceptable test results but the surface as seen under the microscope is rough. Since microscopic examination was an essential part of the program, all of the samples were further chemically polished with the following solution:

Phosphoric acid - 75 parts
Sulfuric acid --- 25 parts
Nitric acid ----- 5 parts

The specimens were placed in this solution and heated to 80°C for three minutes. With this final treatment a surface suitable for microscopic examination was obtained. The surface condition of a typical electropolished sample is shown in Figure 4.

The corrosion-fatigue testing was carried out as shown in Figure 5. A plastic container was placed around the central test section of the fatigue sample. With the sample thus enclosed in a chamber, the corrosive solution, 0.5 per cent by weight NaCl dissolved in distilled water, was introduced through the top of the fixture and exited through the bottom. The unit is designed so that the corrosive solution can be pumped continuously through the sample chamber in a closed circuit. To avoid possible contamination and concentration changes, this arrangement was not used; rather, only fresh solution was allowed to drip onto the specimen and after exiting through the bottom of the fixture the solution was dumped. Lorkovic and Daniels (47), have shown that as long as the surface of a corrosion-fatigue specimen was kept wet with the corrosive solution, the rate of application of the solution did not materially affect the test results. Therefore, all of the corrosion-fatigue tests were conducted with an approximate rate of one drop per second of the corrosion solution falling on the test section of the samples. This rate was maintained by periodic adjustment during the tests. No corrosion-fatigue test could be conducted without continual attendance. It was found that, even though connected to a constant voltage source, the motor speed would tend to increase during the period of the test. This came about not only because of the increasing temperature of the motor bearings and oil, but also due to the "breaking in" of the seals in the corrosion fixture. Therefore, in all of the

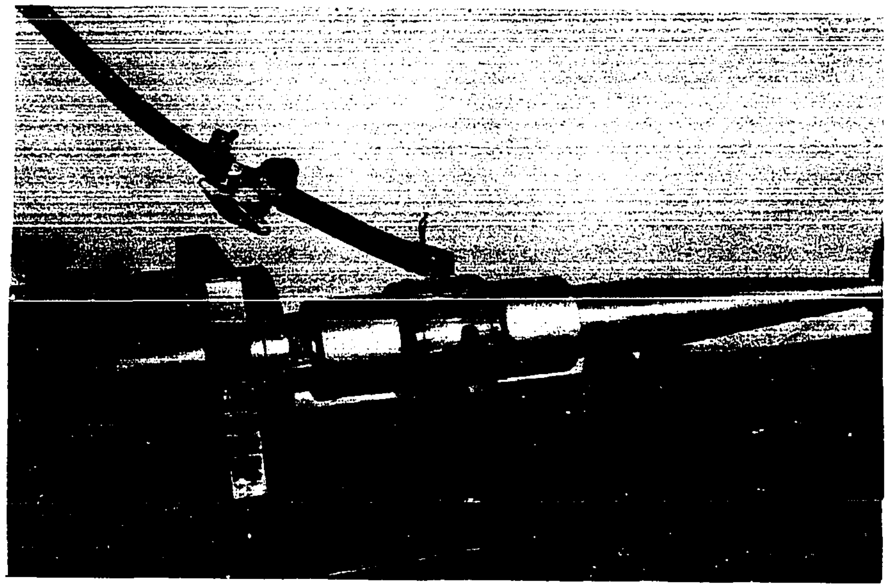


Figure 5. Corrosion-Fatigue Fixture in Place on Fatigue Machine. Stopcock Regulates Rate of Corrosion Solution Application

rotating beam tests, in fatigue and corrosion-fatigue, the speed of testing was checked at frequent intervals and was adjusted as necessary to maintain a reasonably constant rate of stress application.

Attempts were made at the start of this investigation to follow the progress of cracks on the surface of the specimens with a microscope in order to determine their rates of propagation on the surface. Very small cracks could be seen on the fatigue samples and their progress followed under certain conditions. Under other conditions, as will be seen later, multiple cracking occurred and the phrase "surface crack propagation rate" is ambiguous. In the corrosion-fatigue tests, the corrosion of the surface by the salt solution so masked the initiation and propagation of the corrosion-fatigue cracks that it was not possible to see and measure the cracks on the surface during the tests. In many cases the specimen would fail, that is, machine cut-off would occur, without the crack or cracks which caused the failure becoming observable on the surface. While surface cleaning during the tests might have made these cracks visible, this procedure would have had an effect on the life of the samples thus treated, and, therefore, this was not done. A glance at any of the corrosion-fatigue sample pictures that follow in Chapter III will show the surface condition described. Since multiple cracking is a characteristic of corrosion-fatigue, the ambiguity of reporting crack propagation rates applies here as it does to the fatigue samples.

The specimens were run either to their estimated fatigue or corrosion-fatigue lives as determined from the basic S-N curves or to various fractions of these lives using the same curves as a guide. In none of the tests did the specimen fail in the sense that it broke into two pieces. The fatigue machines were equipped with micro-switches which, if the cantilever suspension system engaged in any unusual or large amount of vibration or deflection, tripped and turned off the motor. Since an increase in vibration is one of the signs of the onset of fatigue failure, this increase turns off the machine while the specimen is still whole. In the partial life tests the machine was turned off after the required number of revolutions.

All of the samples could be, and were tested to determine the residual tensile strength after fatigue and corrosion-fatigue testing. These data were obtained on an Instron tensile tester. All of the rotating beam specimens were microscopically examined on both the outside specimen surface and on the fracture surface. Part of each sample was mounted to permit the metallographic examination of a longitudinal cross section. This cross section was cut where possible through areas of fatigue, corrosion-fatigue, or other major crack areas.

Plate Flexure Testing

The plate flexure fatigue tests were conducted on a Krouse type plate flexure machine. The configuration of the specimens used in this program is shown in Figure 6. The wide end of the specimen is clamped to a fixed mount in the machine and the other end to an eccentric crank adjusted to give the required bending stress. The crank is turned by a variable speed drive. All of the plate tests were conducted under conditions of completely reversed bending with a zero mean fiber stress. Because of the specimen design and its attachment to the machine, the central section, bounded by straight sides, is under a uniform stress.

For the corrosion-fatigue tests, the central section was covered with a heavy wool cloth that moved with the specimen. A distilled water solution of 3% NaCl was used for all of the plate corrosion-fatigue tests. This solution was dripped onto the felt at a rate sufficient to maintain saturation. This rate was approximately 10 drops per minute, or one liter per day.

Using this technique, it was not possible to maintain a uniform concentration of the corrosive solution over the complete length of the specimen at all times. The salt concentration of the solution increased in the first 3 or 4 hours of testing to a point of saturation at the fixed end of the specimen and salt started to crystallize out on the mount and on the adjacent regions of felt. These regions did not include any portion of the test section, but it must be assumed that the salt concentration along the specimen length was higher than the initial value and that concentration gradients may have existed. For low-stress level tests

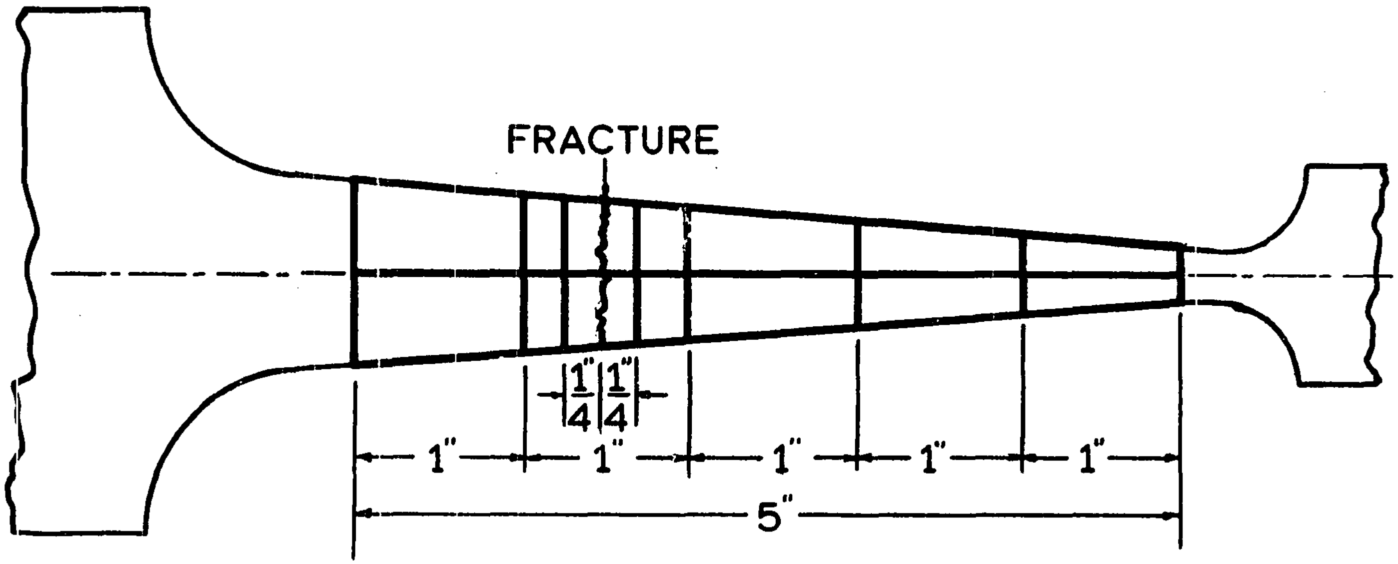


Figure 6. Sectioning of Plate Flexure Specimens for Microscopic Examination. Observed Sections Heavily Outlined.

where the length of the test periods reached several days, the NaCl concentration may have increased considerably due to evaporation. Lorkovic, Varallyay and Daniels (48), have shown that an increase in salt concentration beyond 3 per cent has little effect on the corrosion-fatigue life of specimens tested in rotating bending. These data are shown in Figure 7.

For the "dry" samples, the humidity changes and the salt thrown into the air from the corrosion-fatigue tests might have significantly effected the results. For these reasons, specimens tested under "dry" conditions were coated with a thin film of oil. The rotating beam tests were not conducted in the same laboratory in which the plate flexure tests were run.

The variables examined in the plate tests were the frequency of testing, the magnitude of the fiber stress, and the corrosive environment. The two frequencies chosen were 1200 and 1900 cycles per minute. These speeds represented the extremes of the testing range available with the machine used.

The results of the investigation cited above (48), shown as the solid lines in Figure 8, were used as a basis for the selection of the stresses used here. As in the rotating beam tests, stresses were chosen so as to result in the same approximate cycles to failure for both the fatigue and corrosion-fatigue conditions. These stresses are shown in the figure. Four specimens were tested at each of the six stress levels, two each at the two testing speeds.

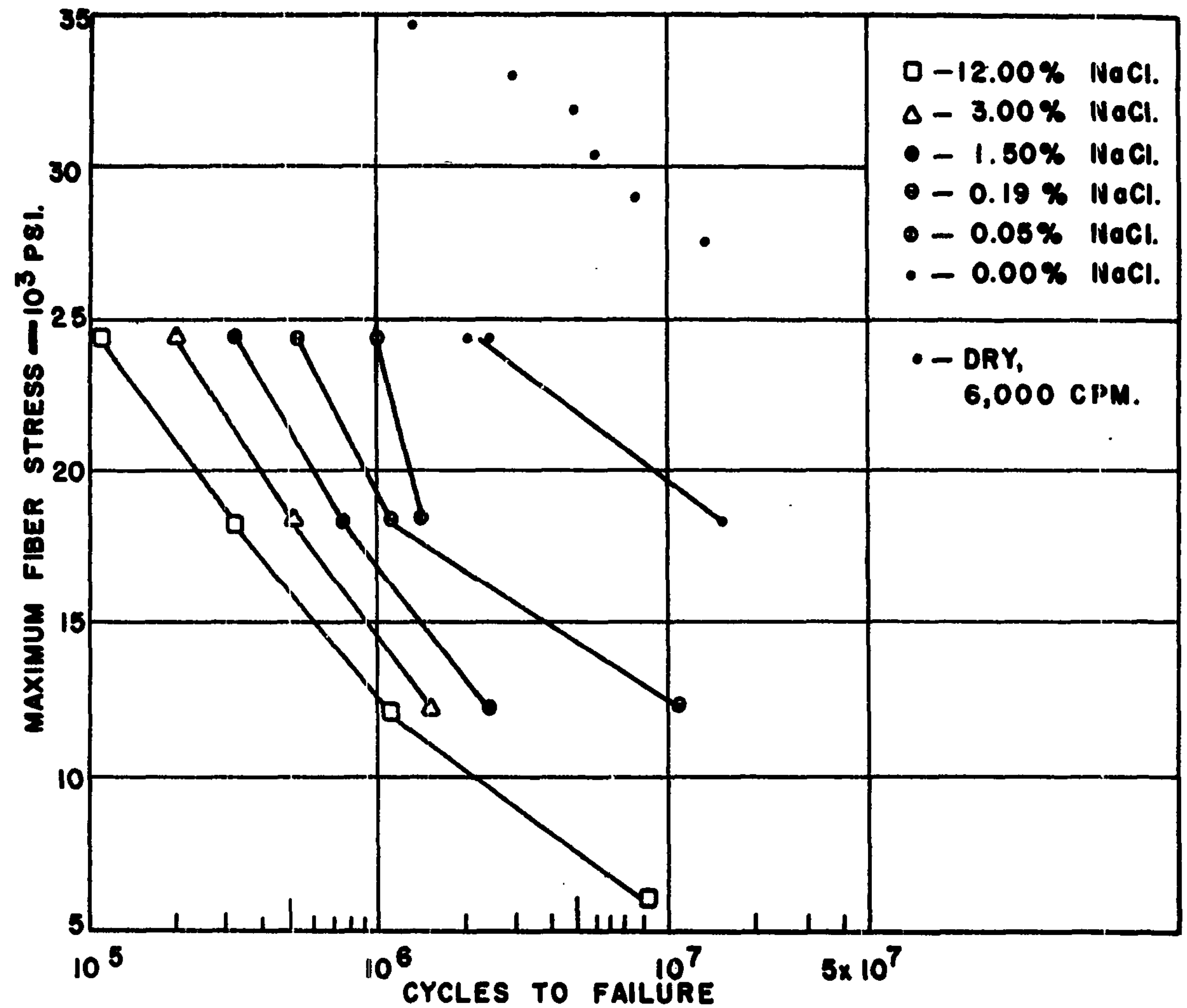


Figure 7. Corrosion-Fatigue Data, 2024-T4 Aluminum Alloy, Rotating Bending Test 3,000 rpm, for Various Solutions of NaCl in Water

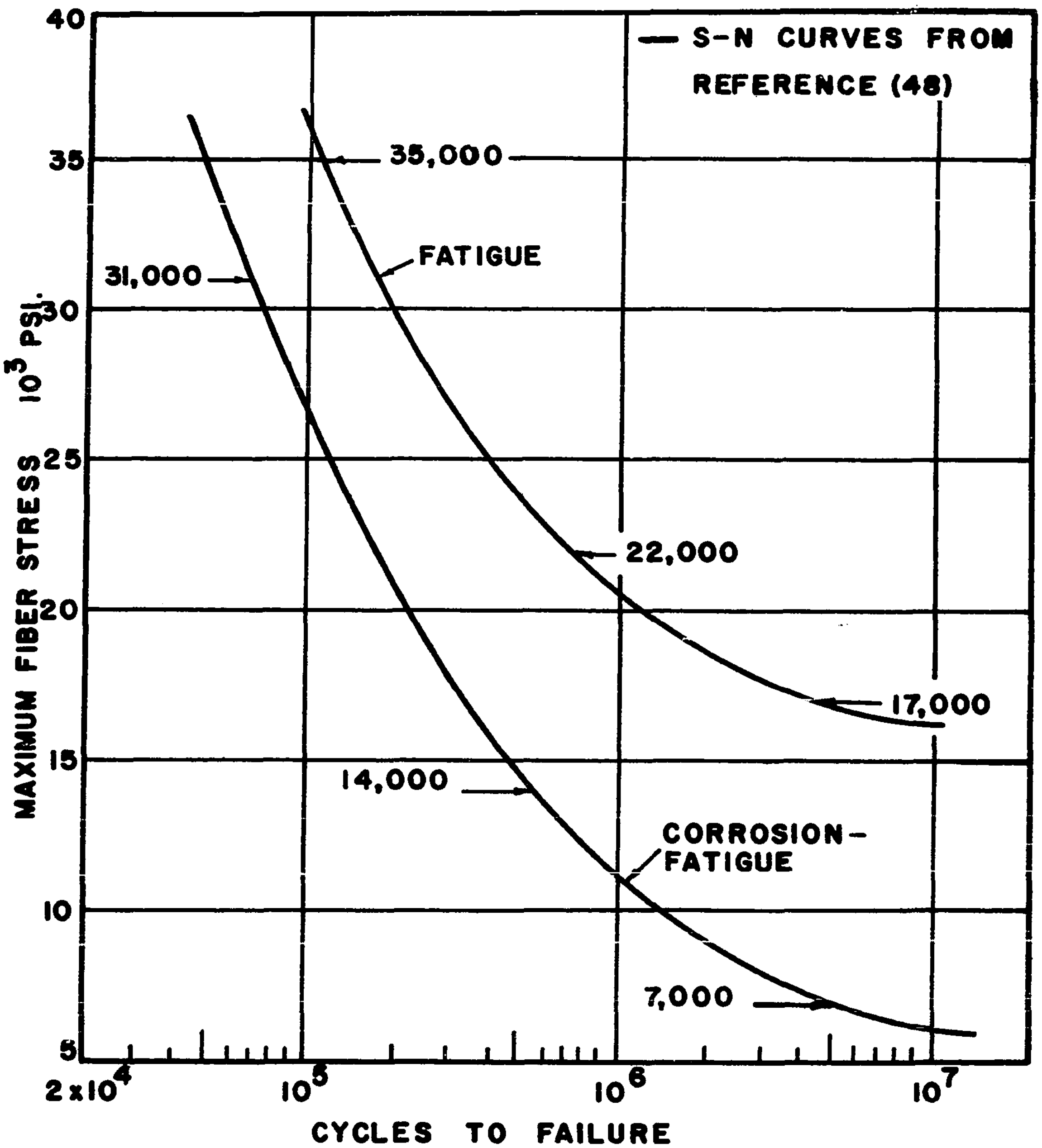


Figure 8. Fatigue and Corrosion-Fatigue Curves for Plate Flexure Tests Showing Stress Levels Chosen for Investigation

After specimen failure, those tested in the NaCl environment were washed under running water to remove salt deposits from the surface. After drying, foreign materials were removed with a soft brush. The fatigue specimens were degreased with alcohol.

Figure 6, which shows the configuration of the plate specimen, also shows where the specimens were sectioned and the areas microscopically examined. Each of the heavy-lined areas were examined, one at a time, microscopically. Adjacent sections, because of the cutting and polishing procedures, were about 2.5 - 3.5 millimeters away from each other. This distance seemed large enough to minimize the probability of recording the same crack with respect to both sections.

The total area of sample cross section examined in the transverse direction was about 11 to 12 cm^2 per specimen, with the corresponding values for the longitudinal direction being 21 to 23 cm^2.

Microscopic examination of the specimen cross sections were carried out at 200 diameters, and defects were measured with a millimeter-scale rule on the mat screen of the metallograph. Both the frequency and type of crack damage were recorded.

CHAPTER III

EXPERIMENTAL RESULTS

Rotating Beam Specimens

Tensile samples were machined from each bar of material used to make fatigue specimens to determine the tensile properties of the alloy. These specimens were machined from each end and the middle of the bars from which the fatigue specimens were obtained. The tensile results, obtained on an Instron Tester, are shown in Table II. Typical mechanical property minimums for the alloy are noted at the bottom of the table. These data for 2024-T4 aluminum alloy are taken from the Metals Handbook (16). All of the yield strengths and elongations exceeded these minimums and only one of the tensile strengths was below the minimum by 1 1/2 per cent. Since all of the other mechanical properties of this bar were above the minimum specification, and since this percentage below the minimum was not excessive, this bar was not rejected. In this regard it should be mentioned that the minimum mechanical properties as stated in the Metals Handbook (16) for this alloy are the averages found for a large number of forms. For example, in sheet form, a very thin sheet will have lower acceptable mechanical properties than a thicker

TABLE II

MECHANICAL PROPERTIES OF 2024-T4 ALUMINUM BAR STOCK

Spec. No.	Yield Strength psi.	Tensile Strength psi.	Elongation in 1 1/2 in. per cent
1	49,500	68,800	33
3	49,800	68,800	29
17	49,000	68,600	29
101	50,000	69,800	31
117	50,000	68,600	29
132	50,000	69,200	29
201	50,000	68,800	27
217	50,000	68,800	28
233	50,000	69,000	27
301	51,000	71,000	29
317	51,000	71,500	29
333	50,000	70,800	30
401	51,200	71,600	29
417	51,000	72,000	29
433	51,000	69,000	29
501	51,000	69,400	29
517	49,000	68,600	29
533	50,000	68,600	27
601	50,000	68,800	29
617	51,000	70,000	29
634	49,000	68,400	29
702	51,000	70,200	28
717	49,000	68,400	29
732	51,000	70,000	30
801	48,000	67,000	27
817	49,400	69,000	29
833	49,500	69,500	33
901	52,000	71,000	30
917	53,000	72,400	31
933	53,000	72,300	31
Typical values for 2024-T4 extruded bar from Metals Handbook (16)			
	47,000 min.	68,000 min.	19-20 min.

sheet. Therefore, these minimums can be treated in a somewhat general way.

The basic S-N fatigue curve was determined in rotating bending and the results are shown in Table III and plotted

TABLE III

FATIGUE VALUES FOR BASIC CURVE 2024-T4 ALUMINUM ALLOY, ROTATING BENDING, 3,000 CPM

Spec. No.	Maximum Fiber Stress, psi.	Cycles to Failure	Residual Tensile Strength, psi.
		Fatigue Curve	
16	60,500	7,400	(1)
127	54,700	17,300	32,800
606	49,700	37,700	(1)
213	44,900	65,300	23,900
614	39,900	126,000	19,600
329	34,800	343,800	16,550
308	29,700	770,300	19,400
528	27,000	1,504,000	15,800
223	24,900	10,229,000 (2)	71,300

(1) Specimen not tensile tested, broken by hand.

(2) Test stopped at this point. Specimen did not fail.

in Figure 9. This figure also shows the experimental scatter band as determined for this alloy and reported by Templin (4). The values for this study are well within this fatigue band. These values further exhibit a smoothness and consistency that can be misleading; that is, one could well ask why such a wide scatter is exhibited if all data are as consistent as was here determined. Simply stated, since all of the specimens were polished and run within a day or two, the conditions of testing would be considered more consistent than if points were determined from samples polished at different

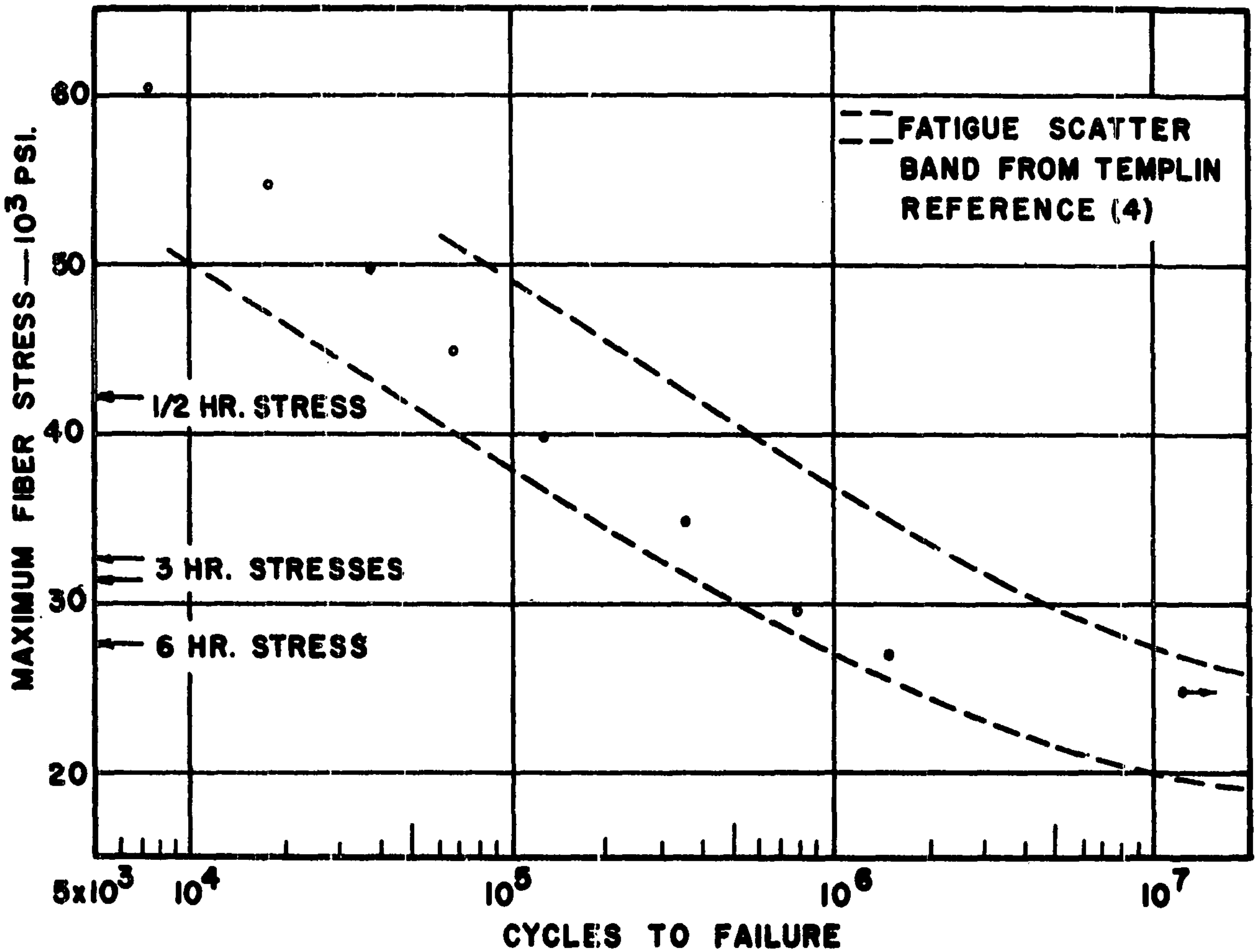


Figure 9. Basic Fatigue Curve, 2024-T4 Aluminum Alloy Bar, Rotating Bending Tests, 3,000 rpm, Showing Stresses Chosen for Investigation

times and tested on different machines over a longer span of time. This consistency in the test procedure usually can account for higher than normal consistency in fatigue test results.

The fatigue limit for 2024-T4 Aluminum alloy, from the Metals Handbook, is 20,000 psi after a test of 5 x 10^8 cycles. This value was determined, as were the tests conducted in this investigation, on an R. R. Moore rotating beam machine. No attempt was made to determine if the specific material used here met or exceeded this specification. At the testing speed used in this investigation, 3,000 rpm, a single test to this stated limit would require almost four months. However, from the curve in Figure 9, it would appear that the value of 20,000 psi at 5 x 10^8 cycles would either be met or exceeded.

The S-N curve for corrosion-fatigue was determined in a similar manner to the fatigue curve and these results are shown in Table IV and are plotted in Figure 10. The

TABLE IV

CORROSION-FATIGUE VALUES FOR BASIC CURVE, 2024-T4 ALUMINUM ALLOY, ROTATING BENDING, 3,000 CPM, ENVIRONMENT SOLUTION OF 0.5 PER CENT NaCl

Spec. No.	Maximum Fiber Stress, psi.	Cycles to Failure	Residual Tensile Strength, psi.
124	59,500	4,000	36,400
425	48,500	11,700	33,600
306	39,900	28,600	19,600
524	29,000	76,700	18,000
322	25,200	153,200	14,500
622	20,000	261,300	15,050
219	15,200	841,500	6,200

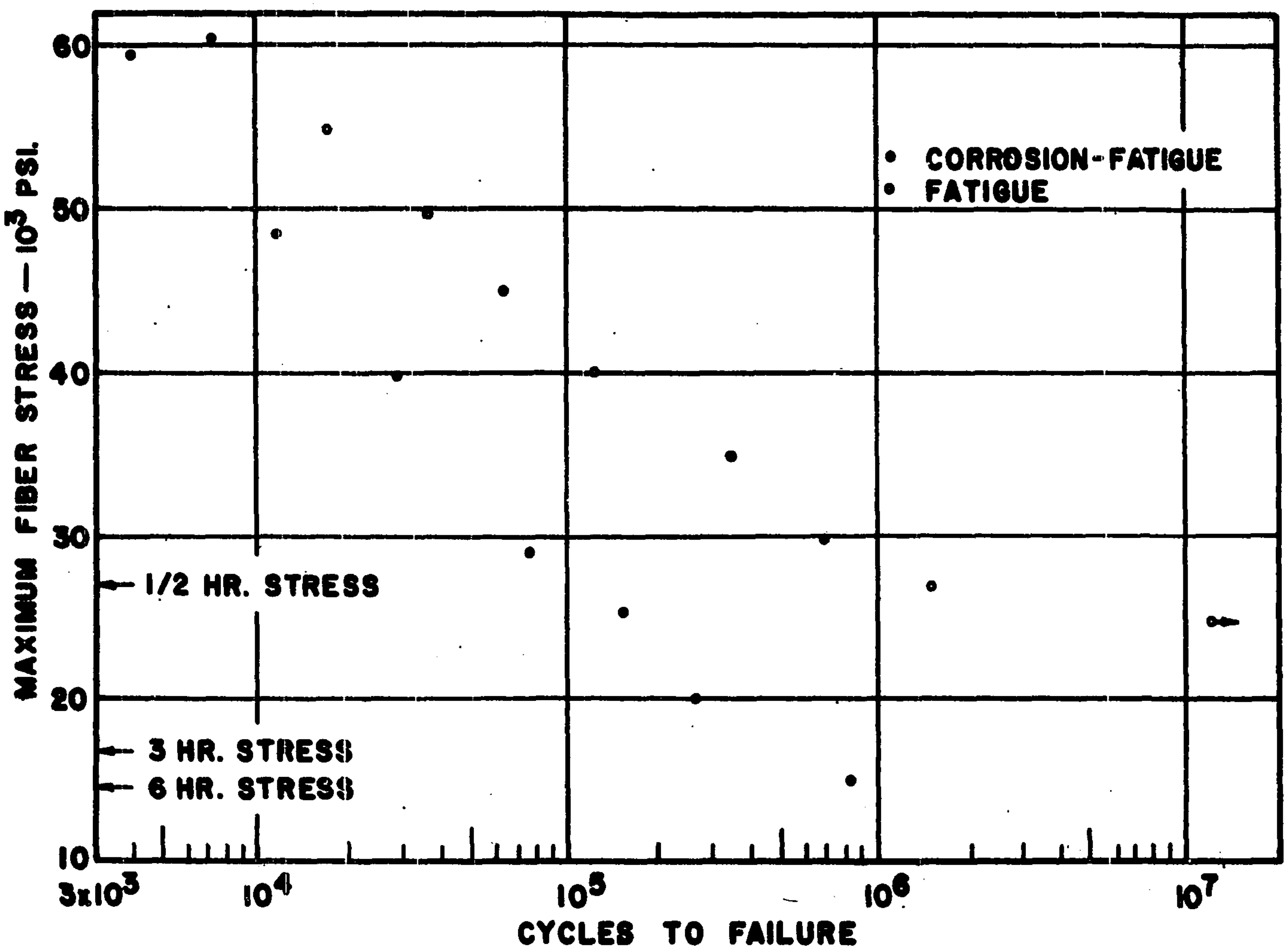


Figure 10. Basic Corrosion-Fatigue Curve, 2024-T4 Aluminum Alloy Bar, 3,000 rpm Rotating Beam Tests, 0.5% NaCl Solution

same remarks apply to the corrosion-fatigue curve as to its smoothness and consistency as were applied to the fatigue curve. No attempt was made to obtain very long-time values for this condition since values beyond approximately 6 hours or 10^6 cycles were not of interest for this experimental program.

Except for two specimens which were broken by hand, all of the samples used in determining the two basic fatigue curves were tensile tested on the Instron. The residual tensile strength after fatigue or corrosion-fatigue to a given percentage of anticipated life is shown in Tables III and IV.

The three stress levels chosen for investigation correspond to times-to-failure of approximately one-half hour, three and six hours. The corresponding cycles to failure were thus approximately 90,000, 500,000 and 1,000,000 cycles. These values are shown on the basic curves, Figures 9 and 10.

The results of this study are reported in order from the lowest stressed of the dry fatigue samples to the most highly stressed of the corrosion-fatigue samples. The fatigue, corrosion-fatigue and tensile data for all of the rotating beam specimens are shown in Tables V and VI.

TABLE V

FATIGUE RESULTS--2024-T4 ALUMINUM ALLOY
ROTATING BENDING, 3,000 CPM

Spec. No.	Maximum Fiber Stress, psi.	Cycles*	Residual Tensile Strength, psi.
	6 Hours or 1,000,000 Cycles		
103	27,700	1,247,400	13,800
707	27,600	833,300	63,000
503	27,600	666,600	74,000
	3 Hours or 500,000 Cycles		
110	32,700	479,600	18,850
518	32,500	334,000	58,000
406	32,500	250,000	72,200
331	31,400	163,000	69,500
203	31,400	84,000	71,600
	1/2 Hour or 90,000 Cycles		
28	42,200	99,800	16,000
529	42,400	75,000	59,500
626	42,400	60,000	61,000
526	42,500	45,000	68,000

*Only the first specimen in each series was run to machine cut-off (failure).

TABLE VI

CORROSION-FATIGUE RESULTS--2024-T4 ALUMINUM ALLOY
ROTATING BENDING, 3,000 CPM
0.5 PER CENT NaCl SOLUTION

Spec. No.	Maximum Fiber Stress, psi.	Cycles*	Residual Tensile Strength, psi.
	6 Hour or 1,000,000 Cycles		
713	14,800	1,034,600	33,000
310	14,750	833,300	29,800
615	14,900	666,600	56,400
26	14,900	500,000	61,600
514	14,700	333,300	71,000
	3 Hour or 500,000 Cycles		
231	16,600	504,800	4,600
327	17,000	416,000	46,000
215	16,500	333,300	67,000
10	17,000	250,000	68,000
230	17,000	166,000	68,000
	1/2 Hour or 90,000 Cycles		
334	27,000	103,200	27,100
832	27,000	85,300	60,900
332	27,000	66,600	73,000

*Only the first specimen in each series was run to machine cut-off (failure).

Macroscopic Examination - Rotating Beam Specimens

Dry Fatigue, Six Hour Series

Specimen No. 103, which had a life of approximately 1.25×10^6 cycles was the most classic in appearance of all the fatigue samples. In the sense used here, classic refers to usual textbook type of rotating beam fatigue failure. Typically, this type of failure is shown to consist of only one area of fatigue which starts from a well defined point. After failure, the fatigued area appears fan-shaped, the apex of the "fan" being the starting point of the fatigue crack. The entire fatigued area is usually flat and runs perpendicular to the applied stress.

The fatigued area, as seen on this specimen, extended over approximately 70 per cent of the cross sectional area. Figure 11 shows the appearance of this area which includes all of the left hand portion of the specimen and almost one-half of the right. The line of demarcation between the fatigue and the tensile fracture can be faintly seen as a line extending from about 6 o'clock on the figure to the dark area around 1 o'clock. Since tensile testing will also help to show up surface fatigue cracking other than the main crack, Figure 12, is included to show that this specimen had no other than the main crack which caused failure. This photograph was taken at the point of tensile failure, which in Figure 11, would be the lower right hand portion. The specimen was in tension in this area and any surface fatigue

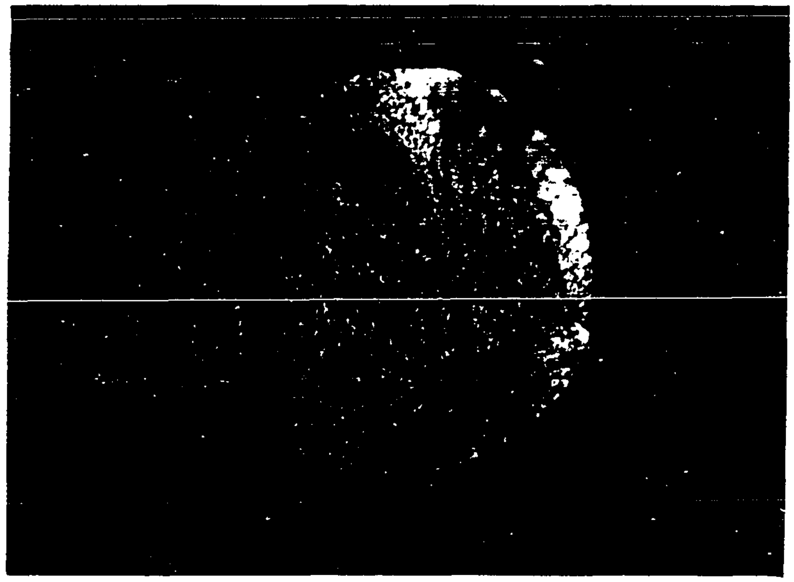


Figure 11. Specimen No. 103, Fracture Surface. Flat, Almost Featureless Area on Left

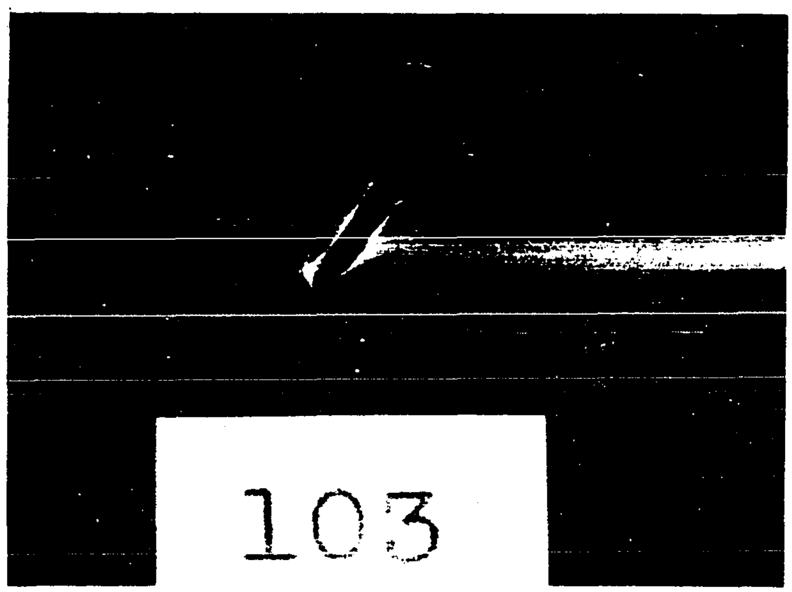


Figure 12. Specimen No. 103, Tensile Fracture and Featureless Specimen Surface

cracking would tend to open up whereas if any cracking occurred in the volume adjacent to the fatigued area this would not occur, as this volume was not in tension during the tensile test.

Reference will be made hereafter to the specimen surface. This should be understood to mean the polished surface of the specimen to which the atmosphere of whatever kind is applied and where the fatigue or corrosion-fatigue cracking starts. The phrase fracture surface or failure surface should be understood to mean the surface revealed after tensile testing and includes the tensile fracture and the fatigue fracture or corrosion-fatigue fracture areas, if any, to complete the cross-section. These terms are never used interchangeably.

The second specimen in this group, No. 707, was run to approximately five-sixths of its fatigue life as determined by the previous sample. From the residual tensile strength, it would appear that not much fatigue occurred during the more than 800,000 cycles of fatigue applied to the sample. Only one small area of fatigue could be seen on the fracture surface, it is the light appearing area in Figure 13.

This again could be considered a classical type of fatigue in that the fracture probably started at one point on the surface and would continue to grow out in a fan or crescent moon shaped area. The area as shown in Figure 13 represents about 5 per cent of the total cross-sectional

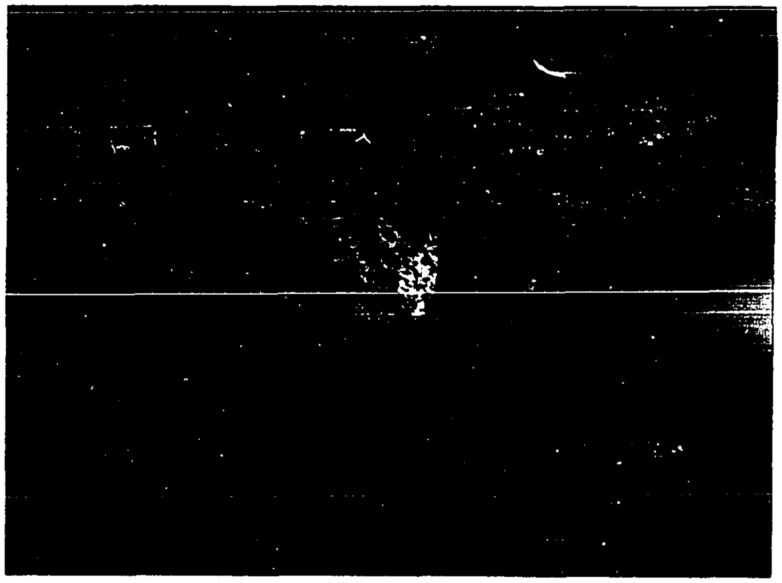


Figure 13. Specimen No. 707, Small Fan-Shaped Area of Fatigue on Right

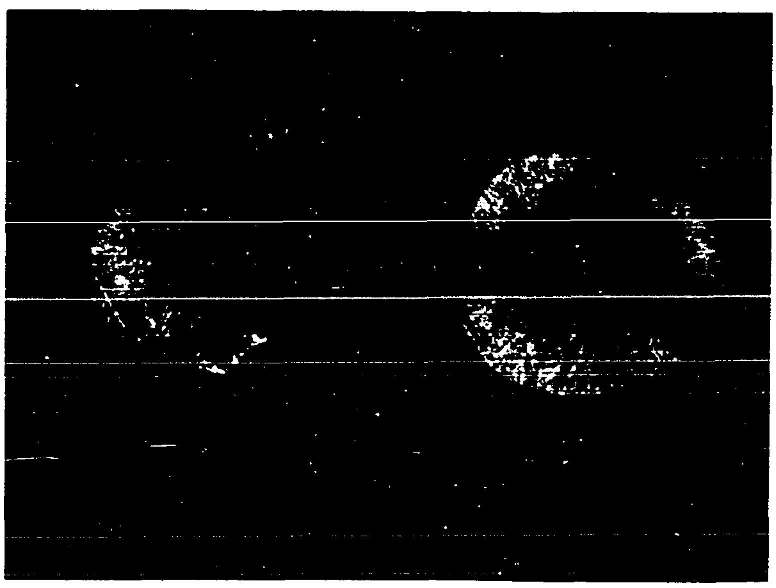


Figure 14. Specimen No. 503, Tensile Fracture. Almost Symmetrical Cup and Cone

area of the specimen. Even though the residual tensile strength was a high 63,000 psi, no secondary fatigue cracking was observed on the specimen surface.

The last specimen in this series, No. 503, had a residual tensile strength of 74,000 psi. It was, in effect, an unfatigued specimen, even though it received two-thirds of the stress cycles necessary to fail specimen No. 103. The fracture surface of this sample contained no evidence of fatigue damage, and there was no evidence of fatigue cracks elsewhere on the specimen surface. In fact, as shown in Figure 14, the tensile fracture appeared as a near perfect cup and cone, the classical tensile failure for a ductile material.

Dry Fatigue, Three Hour Series

It is with this series of dry fatigue tests that the results begin to diverge from classical fatigue behavior in that some of the characteristics of corrosion-fatigue begin to appear.

On the first of the three hour samples, No. 110, the tensile fracture opened up three separate and distinct areas or layers of fatigue damage. That is, three fatigue cracks began during the test and continued to grow inward during the test. An estimate of the fatigued area on the fracture surface would be about 30 per cent. It should be realized that this value is ambiguous in that more than one fatigue area is involved and that these areas might and do overlap. Unless only one fatigue crack or area is involved, this ambiguity will be present.

Specimen No. 518 was run to approximately two-thirds of the fatigue life at this stress and also revealed the multiple cracking apparent on the previous sample. Figure 15 shows a small fan-shaped area of fatigue on this sample. It amounts to just a few per cent of the cross-sectional area. Even though it is only a small area of the sample, the fatigue cracking exists on at least two levels. A little prong from the upper level, which has been twisted up slightly during the tensile testing, is seen in the photograph. The area at approximately 8 o'clock is one area of fatigue; the smaller area above the little protrusion is another. These areas are separated by a step of about 1/64th of an inch running parallel with the specimen axis.

Examination of the specimen surface revealed two more fatigue cracks which opened up during the tensile test. One was about one-half inch away from the fracture itself, the second about 180 degrees from the first. Thus a total of at least four fatigue cracks started, although the last two did not contribute in any way to the tensile failure.

The last sample in this series, No. 406, run to 50 per cent of anticipated life, failed in a completely ductile manner during tensile testing. No evidence was found of any fatigue cracking on the fracture surface. There was the slightest hint of a fatigue crack on the specimen surface,

Figure 15. Specimen No. 518. Small Fan-Shaped Two-Layered Fatigue Area

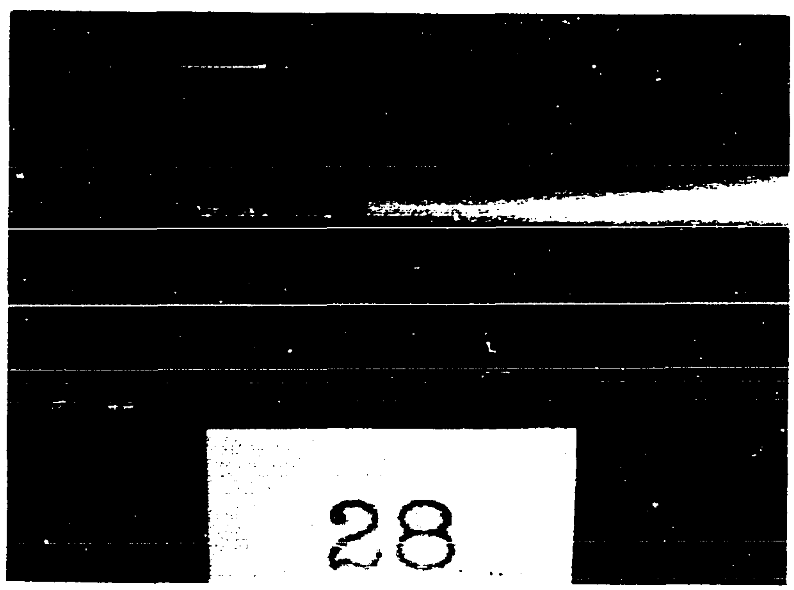


Figure 16. Specimen No. 28, Multi-Layered Fatigue Crack

but with a residual tensile strength of 72,000 psi, it apparently had no effect on the tensile strength.

Dry Fatigue, One-Half Hour Series

This series was most notably different from the six hour fatigue series. Specimen No. 28 was the first of this series and had a life of just under 100,000 cycles. This specimen showed, after tensile testing, a fracture area completely ringed with fatigue cracks with a region of tensile failure in the center. The fatigued areas here are notable in that they are on multiple levels. Figure 16 shows this multiple level fatigue clearly. In this photograph at least five or six definite and separate fatigue fracture levels can be seen. An examination of the fracture surface with a low power magnifier revealed many more levels. The specimen surface also showed other fatigue areas away from this main fracture which were opened up during tensile testing. An estimate of the cross-sectional area fractured in fatigue would be about 20 per cent on this sample.

The second specimen of this series, No. 529, exhibited many of the same characteristics of the previous sample. Again, after tensile testing, the specimen exhibited an almost complete ring of fatigue around the periphery of the fracture surface. A major difference was in the lateral extent of the fracture. As can be seen in Figure 16, the tensile fracture of specimen No. 28 did not exceed about 1/16th of an inch laterally along the sample. In specimen

No. 529, the lateral extent of the fractures was 3/16th of an inch. The displacement of the fracture from level to level during tensile testing suggests the presence of a large number of fatigue cracks. A large number of these cracks opened up during the tensile test because of the large tensile stress required to fracture the sample.

Specimen No. 626 exhibited, on a lesser scale, the characteristics of this entire series. The same multiple level fatigue cracking, extended over a lateral distance of approximately 1/4 of an inch on the specimen surface. The tensile failure was completely ringed with fatigued areas, although these areas jump from level to level on the specimen surface.

The last specimen in this series, No. 526, cycled to one-half of its anticipated fatigue life, appeared from its residual tensile strength, not to have been fatigued at all. However, the fracture surface did contain one small area of fatigue and some evidence was found on the specimen surface of fatigue cracking.

Corrosion-Fatigue, Six Hour Series

The first specimen in this corrosion-fatigue series, No. 713, exhibited many of the features and characteristics which have come to be identified with corrosion-fatigue failures. The fracture surface was not level; it consisted of not one but several layers of corrosion-fatigue. This surface consisted of at least three fairly extensive levels of corrosion-fatigue. In Figure 17, this fracture surface is shown. The definite difference in level between those areas located at about 5, 6, and 7 o'clock is apparent. Proceeding around the surface shown, the area at about 10 o'clock gives slight evidence that it may be a fourth level. The specimen surface showed evidence of other corrosion-fatigue areas, which, because of their location and geometry were not included in the fracture surface. The specimen surface is shown in Figure 18. This was the typical appearance of the specimen surface of most of the corrosion-fatigue samples. The length of sample to which the corrosive solution was applied can be seen along the right hand edge of this figure. The corrosion line is fairly sharp since a rubber gasket fitted around the sample restricted the solution to the center section.

A closer view of the specimen surface is afforded in Figure 19 which shows the salt encrusted surface after the specimen had dried. Each of the black dots represent a pit or hole in the surface. The comet shaped areas of dried salt shown in this photograph, and also seen on other corrosion-fatigue photographs, have no particular significance except that this sample evidently dried while standing on its left hand edge and the salt solution ran down the sample toward the left. It does, however, show clearly the large amount of the solution which remained on the sample after testing. No attempt was made at any time during the testing, except in the very early phases of the program, to remove the

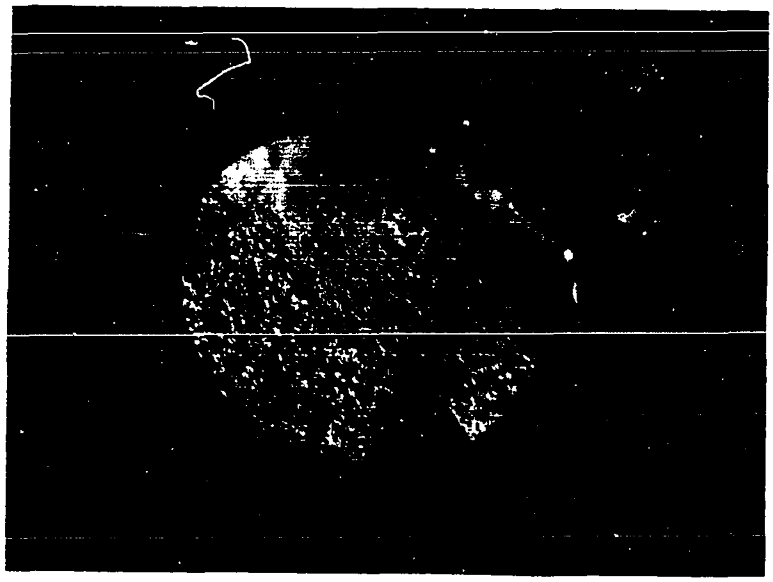


Figure 17. Specimen No. 713, Multilevel Fracture Surface

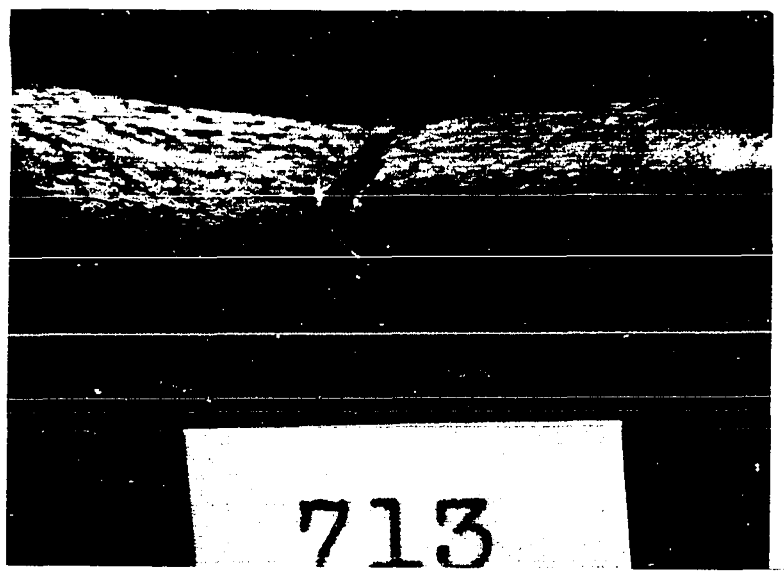


Figure 18. Specimen No. 713. Specimen Surface, Jagged Fracture Periphery

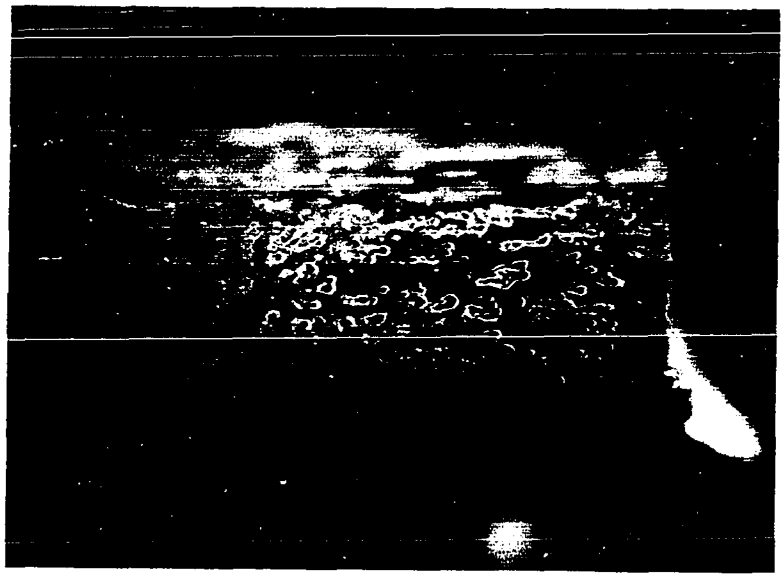


Figure 19. Specimen No. 713. Specimen Surface, Corrosion Pits Surrounded by Dried Salt

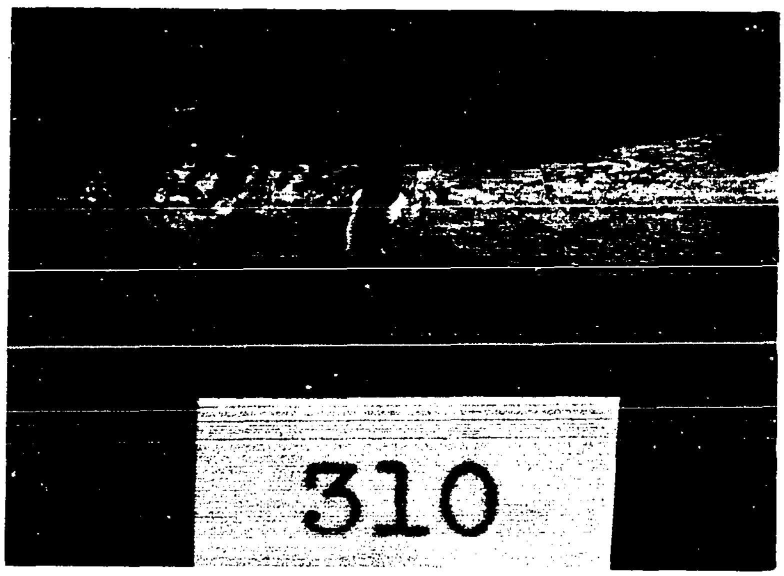


Figure 20. Specimen No. 310. Two Large Corrosion-Fatigue Cracks on Specimen Surface

corrosive solution or the products of the corrosion from the surface of the rotating beam samples. The distribution of the pits on the specimen surface appeared to depend only on the presence of the corrosive solution and not on the stress cycle.

The second sample in this group, No. 310, exhibited on its fracture surface a very large area of flat, almost classical fatigue. This area extended over approximately one-third of the cross-section. The rest of the tensile fracture was ringed by small areas of corrosion-fatigue, each extending only a very short distance into the specimen volume.

This specimen was of interest in that it developed two extensive secondary corrosion-fatigue cracks about 1/4 inch apart on the same side of the specimen surface. These are shown in Figure 20. It is the only specimen that displayed this surprising phenomenon, not only in that the cracks developed away from the area of highest stress, but also in that they developed on the same side of the sample. As can be seen in the photograph, several other corrosion-fatigue cracks were opened up during the tensile testing. This multiple cracking is one of the most characteristic features of corrosion-fatigue.

The third sample, No. 615, showed a large residual tensile strength and its fracture surface mirrored this strength. There were no large areas of corrosion-fatigue cracking; the central tensile fracture was almost completely surrounded by only small patches, each extending just a short distance into the specimen. There was one area which consisted of at least three levels of corrosion-fatigue and did extend into the sample to approximately ten per cent of the specimen diameter. Surface corrosion-fatigue cracking was again apparent.

Specimen No. 26 was run to approximately one-half of its corrosion-fatigue life or about 500,000 cycles at this stress level. There were minor areas of corrosion-fatigue around the fracture surface, their multilevel nature was still apparent. Many corrosion-fatigue cracks were opened up on the specimen surface.

The last specimen in this group, No. 514, had a residual tensile strength above the minimum typical for this alloy. Even so, minor corrosion-fatigue cracks were still apparent and some indication of this appeared on the specimen surface. These may be corrosion pits which were opened by the tensile stress rather than fully developed corrosion-fatigue cracks. In any case, the effect was minor, and the tensile strength did not suffer.

Corrosion-Fatigue, Three Hour Series

The first sample of this series, No. 231, revealed a fracture surface that was more classical in appearance than that of the first sample of the previous series. The fracture surface was nearly level. However, even though appearing level, the multilevel nature of corrosion-fatigue was still present. Only slight evidence of cracking was noted on the specimen surface. This latter observation was misleading, however, considering the low tensile strength remaining, and that the corrosion-fatigue area of the fracture surface was approximately 85 per cent of the total cross-sectional area. It is concluded that surface cracks will not be revealed on samples with corroded surfaces unless large tensile stresses can be applied.

This observation appears to be confirmed in the examination of the second sample in series, No. 327. This sample had a ten-fold increase in the residual tensile strength compared to the previous sample and exhibited more typical corrosion-fatigue features. The tensile fracture surface was jagged and corrosion-fatigue cracks extended completely around the central area of the tensile failure. The jagged edge of this failure is shown in Figure 21. All of the edge shown consists of corrosion-fatigued areas, the tensile failure proceeded by jumping from level to level of the corrosion-fatigue fracture. In lateral extent this failure was approximately 1/8th of an inch. A dozen or more levels of corrosion-fatigue cracks surrounded the periphery of the tensile fracture. The specimen surface exhibited, as would be normal when subjected to this value of tensile stress, a large number of surface cracks. One of the largest of these is seen in Figure 21.

The tensile strength remaining in specimen No. 215 failed to indicate if any corrosion-fatigue damage had occurred. The fracture surface tended toward a cup and cone

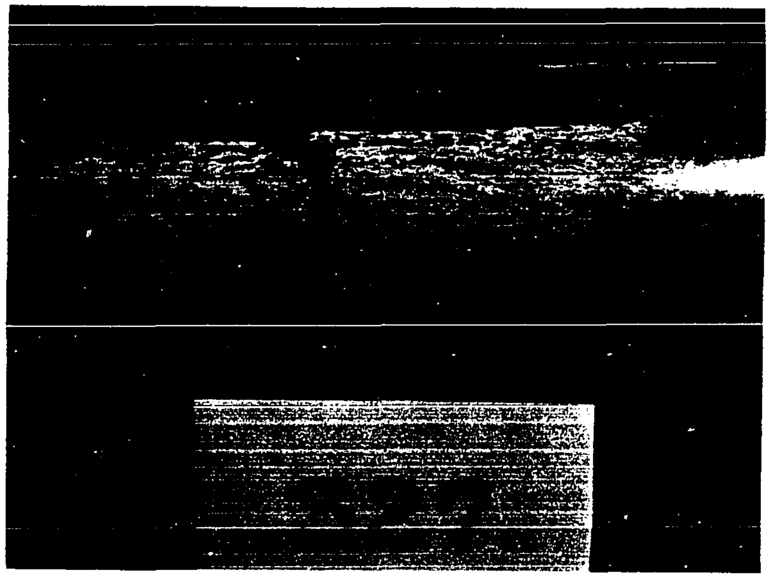


Figure 21. Specimen No. 327. All of the Fracture Edge Shown Goes Through Areas of Corrosion-Fatigue

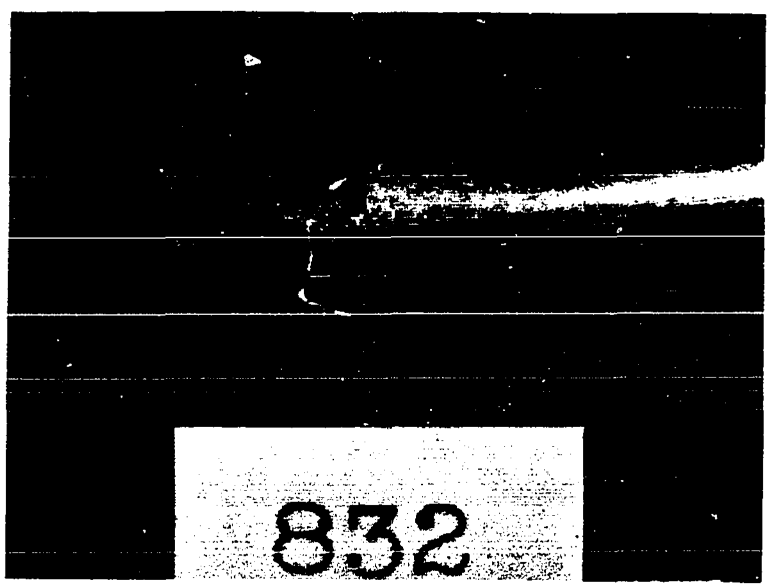


Figure 22. Specimen No. 832. Typical Corrosion-Fatigue Surface Cracking

appearance. No definite corrosion-fatigued areas could be detected on the fracture surface. After tensile testing the specimen surface had a slightly orange peel texture and a suggestion that the corrosion pits were enlarging as previously stated.

Sample No. 10 was run to only one-half of the anticipated corrosion-fatigue life. The same remarks could apply here as to sample No. 215. The corrosion pits may have been opened slightly by the stress during tensile testing. This is suggested again by the surface appearance.

Corrosion-Fatigue, One-Half Hour Series

The first sample of this series, specimen No. 334, with a life of just slightly over 100,000 cycles, exhibited, on its fracture surface, one main area of corrosion-fatigue. This area extended over approximately 40 per cent of the cross-section of the sample and was reasonably level. Again, the fracture surface was not a single level, but consisted of several closely spaced levels. The rest of the fracture surface was ringed by areas of corrosion-fatigue which extended only a small distance into the body of the specimen. Much corrosion-fatigue cracking was found on the specimen surface.

Specimen No. 832, run slightly over 85,000 cycles without failure, exhibited a large residual tensile strength compared to the previous sample. Only shallow corrosion-fatigue cracks were noted around the fracture surface, and these cracks did not completely ring the fracture area. The fracture surface was irregular and jumped, as is characteristic, from corrosion-fatigue area to corrosion-fatigue area. As shown in Figure 22, much corrosion-fatigue cracking was apparent on the surface. This cracking extended approximately 1/4 to 3/8th of an inch along the specimen surface. These figures could be considered typical for most of the samples examined.

The last specimen in this series, No. 332, was cycled to approximately two-thirds of its anticipated corrosion-fatigue life. Its residual tensile strength was well above the minimum for this alloy. Even so, much minor corrosion-fatigue cracking was noted. The areas of corrosion-fatigue seen on the fracture surface extended into the specimen volume to no more than one or two per cent of the diameter. The small cracks were separated by unaffected material so that no "ringing" was possible. Much corrosion-fatigue cracking was seen on the specimen surface.

Microscopic Examination, Rotating Bending Fracture Surfaces

Articles by Ryder (49) and Warke (50) show the recent interest in the microscopic examination of the surfaces of various types of fractures, especially fatigue fractures. Both investigators reported that under certain conditions it was possible to correlate the properties and behavior of the material with the fatigue striations appearing on the fatigued surface. The specimens used in these reported investigations were flat bar stock or plates and the stress pattern applied usually had a positive mean value. For example, a mean stress of 10,000 psi would be employed with a variation from a minimum of 5,000 psi to a maximum of 15,000 psi. This situation would always insure an open fatigue crack. The present study had a mean stress of zero in reversed bending. The maximum fiber stress of the surface of the samples went from its greatest positive or tensile value through zero to its greatest negative or compression value. The effect of this method of loading on the development of a fine structure in striations has not been reported, but it was suspected that a galling action would obliterate fine markings that might appear on the surface. To evaluate this fine structure all of the fractured specimens were examined for the presence of striations subject only to the mechanical limitations of specimen-to-objective lens distances of the metallograph used.

Dry Fatigue, Six Hour Series

A problem in an investigation of this type is the uneven fracture surfaces. This makes for a quality of photomicrograph that will not stand comparison with what one has come to expect. Figure 23 shows the appearance of the fracture surface of specimen No. 707 from the six hour fatigue series. The unevenness of the surface is only too apparent. These difficulties are compounded in that lenses of high magnification, necessary to resolve fine detail, do not

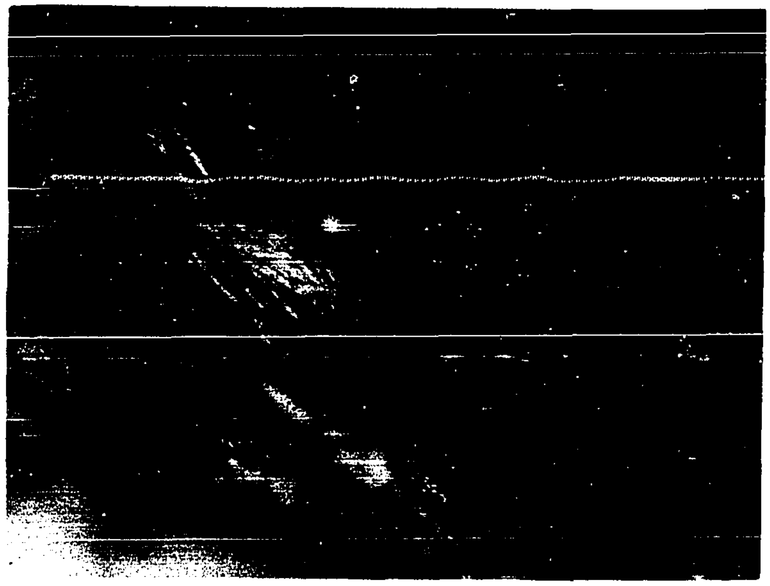


Figure 23. Specimen No. 707. Magnification 500X. Edge of the Fracture Surface

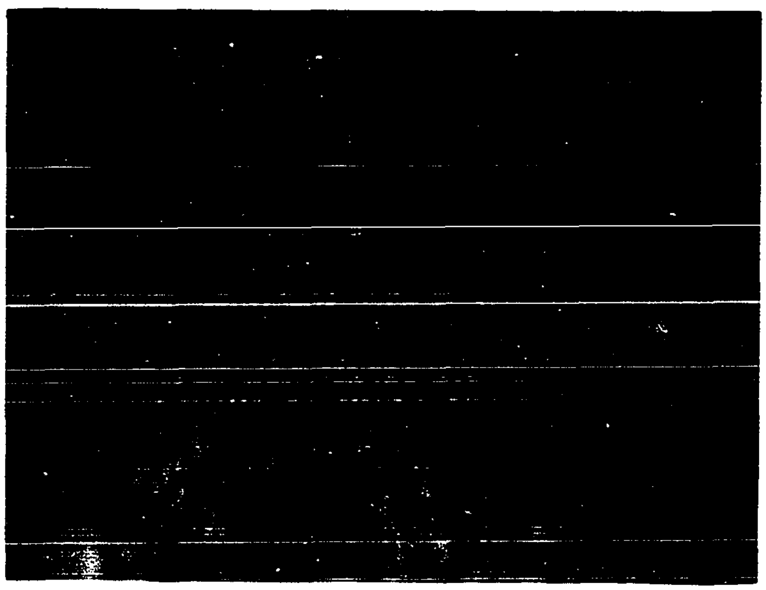


Figure 24. Specimen No. 707. Magnification 1200X. Fan-Like Structure Near Center of Fatigued Area

possess a large depth of focus thus limiting the observer still further. There is a suggestion in Figure 23 of fatigue striations near the bottom center of the field shown. In only a few instances were features found that could be definitely termed striations associated with the advance of the fatigue crack front.

In the visual examination it was possible to overcome somewhat the limitations of both the specimen geometry and the limited depth of focus by selective focus in and out on each surface thereby gaining the maximum of information. It was possible on Specimen 707, on that specific portion shown in Figure 23, to see various areas which have what appear to be fatigue markings but which have no consistent orientation. If one assumes a reasonably simple stress pattern near the surface of the sample, any fatigue striations should be parallel to the surface. If one assumes that the faint markings in Figure 23 are indeed fatigue striations, then the stress pattern must be more complex.

Reference was made previously to certain fatigued areas that had a fan-like appearance. Almost without exception, microscopic examination of these areas revealed a structure like that seen in Figure 24. This sort of feathery appearance is characteristic of the fine detail of the fan-like regions. It can also be seen that there are no striations here. Any small detail would have been ground out of the specimen during the compressive portion of the fatigue cycle.

The next two figures, No's. 25 and 26, were taken on Specimen No. 103. This is one of the few instances where the fatigue striations were definite enough to leave no doubt of their existence. This specimen had a large flat area of fatigue which extended over about 70 per cent of the cross-sectional area of the specimen. The outer edge and most of the rest of this area had a featureless appearance. The crack front of the fatigued area, i.e., that near the region of tensile failure, is the location shown in the figures. This area was the last to be fatigued and was subjected to the least amount of grinding action. The magnification in both cases is well over 1,000X so the extremely small size of the striations is apparent. The striations in both cases appear to be oriented in the same general direction.

Dry Fatigue, Three Hour Series

An examination of the three hour fatigue series revealed no new features not already noted. Only one small spot on Specimen 518 was of sufficient interest to be included as Figure 27. This structure is typical of most of the specimens examined, in that the evidence for striations is marginal. The faint lines, just slightly off the vertical in the figure may or may not be fatigue striations.

Dry Fatigue, One-Half Hour Series

The one-half hour fatigue series failed to show fatigue striations. The edge of Specimen 28, shown in

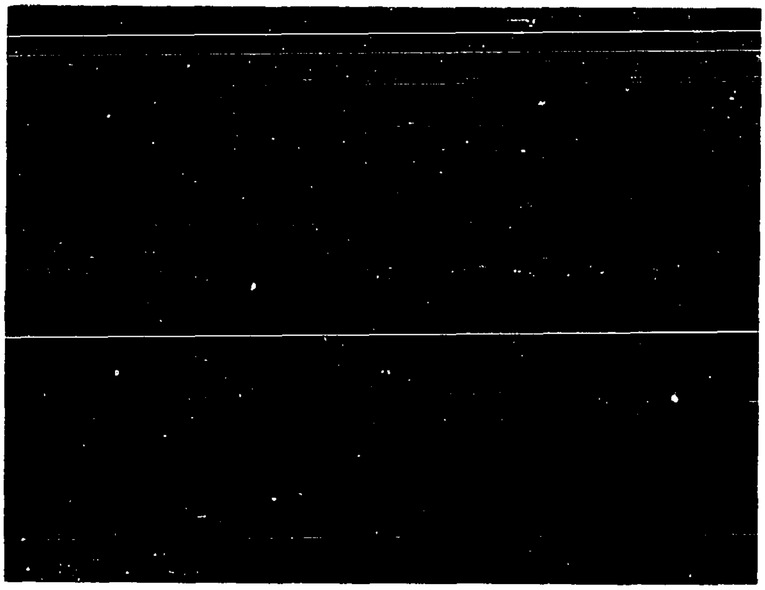


Figure 25. Specimen No. 103. Magnification 1200X
Fatigue Striations

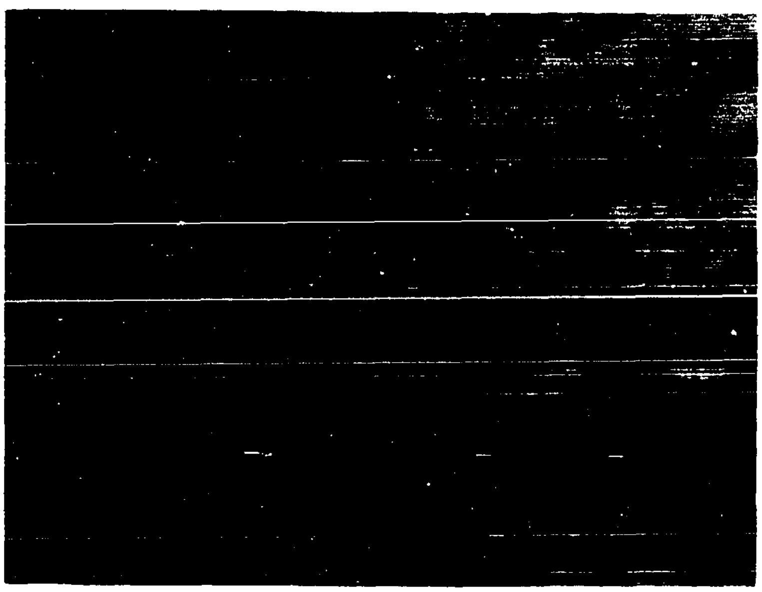


Figure 26. Specimen No. 103. Magnification 1200X
Fatigue Striations

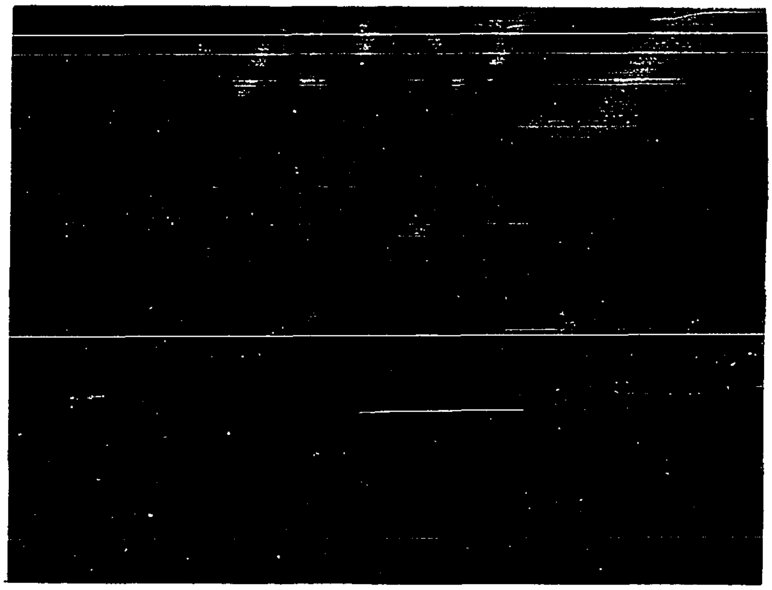


Figure 27. Specimen No. 518. Magnification 1200X
Fatigue Striations

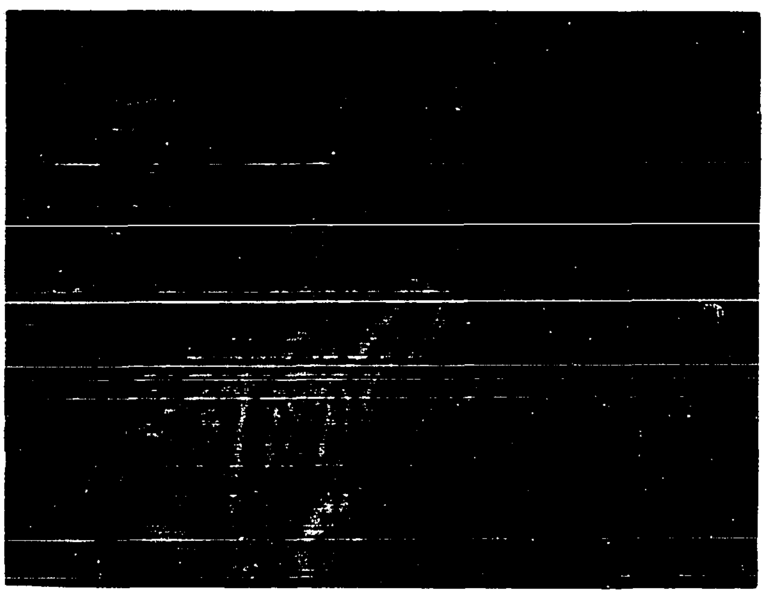


Figure 28. Specimen No. 28. Magnification 1200X
Edge of Fatigued Area

Figure 28, is a comparatively smooth surface due to the compressive grinding that it has received.

Corrosion-Fatigue, Six Hour Series

The corrosion-fatigue samples were distinctive in that their fracture surfaces all contained a large amount of corrosion in the form of pits. A typical example is shown in Figure 29, approximately the center of the corrosion-fatigued area of Specimen 713, the first sample in the six hour corrosion-fatigue series. The corrosion pits show up as black dots liberally sprinkled throughout the area. This region should be compared with the area shown in Figure 23 which, although it contains one or two pits, does reveal the differences between the two surfaces. No unambiguous corrosion-fatigue striations could be found on this sample.

Figure 30 shows the line of demarcation between the corrosion-fatigue area and the tensile failure. Even with problems of specimen unevenness and the lack of photographic depth of field, this line can easily be seen. First, the corrosion pits do not appear in the tensile portion of the fracture surface which has a sparkling, almost iridescent, appearance under the microscope, whereas the corrosion-fatigue areas are darker due to the rubbing which has occurred there.

Figure 31 shows some striations found on Specimen No. 310, a sample run to about 80 per cent of its expected corrosion-fatigue life. These markings were the most

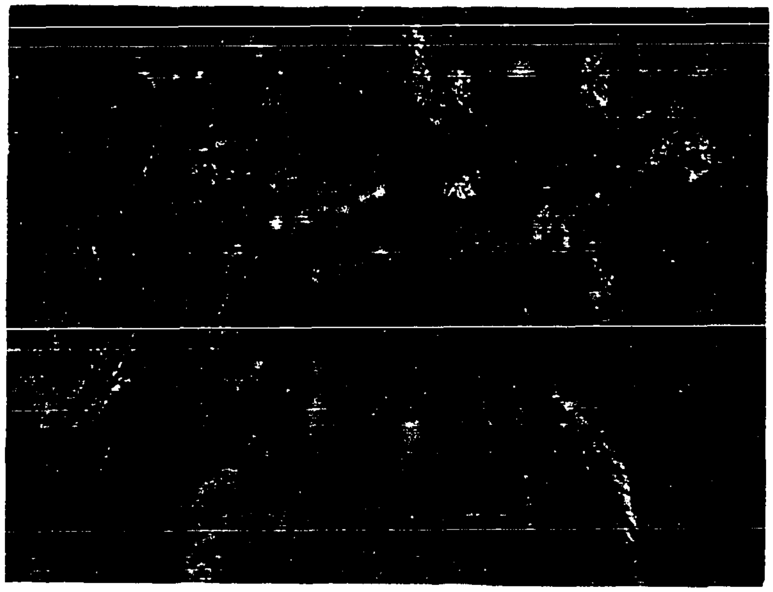


Figure 29. Specimen No. 713. Magnification 500X. Typical Corrosion-Fatigue Striations

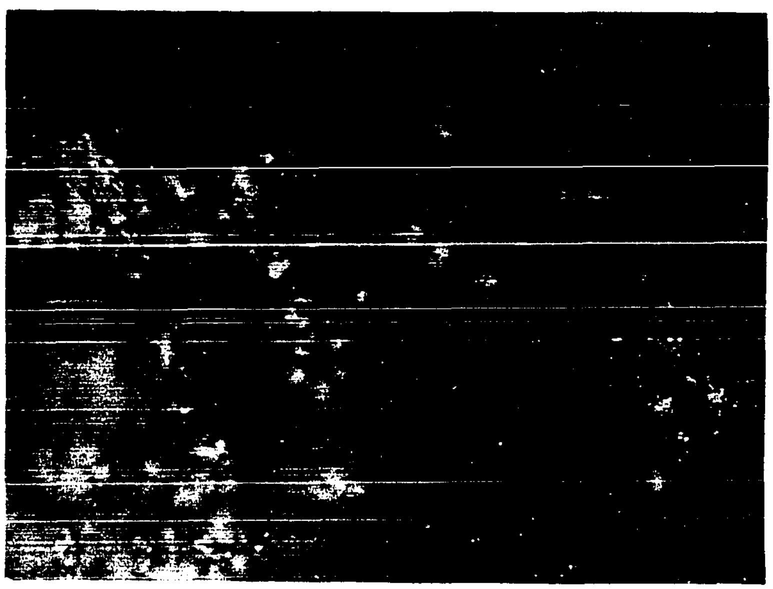


Figure 30. Specimen No. 713. Magnification 500X. Line of Demarcation Between Corrosion-Fatigue and Tensile Failure Area

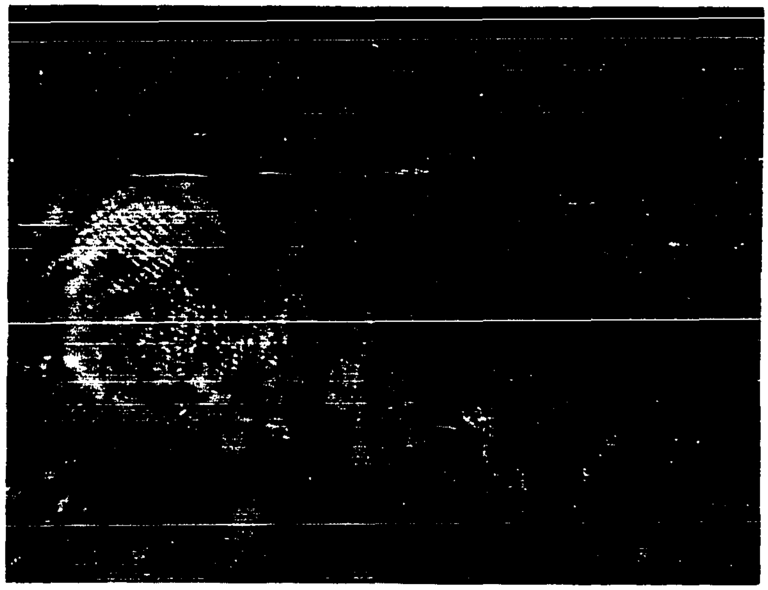


Figure 31. Specimen No. 310. Magnification 500X. Corrosion-Fatigue Striations

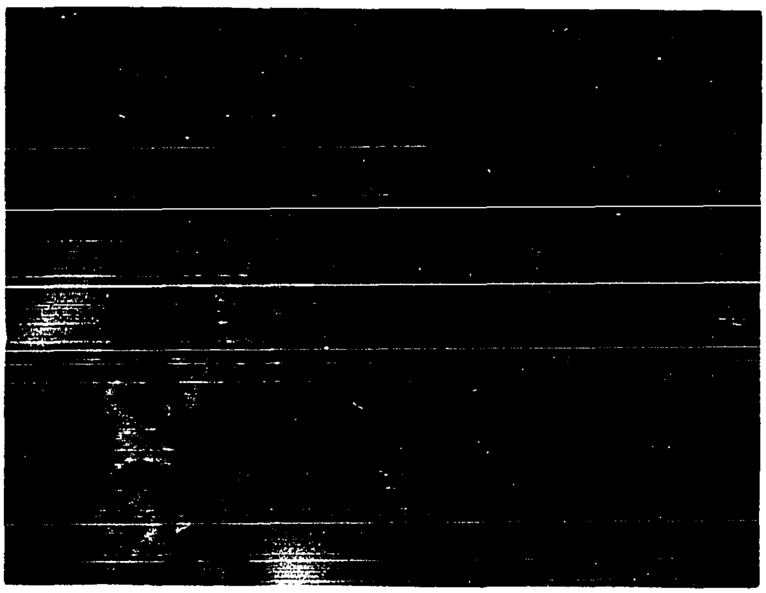


Figure 32. Specimen No. 231. Magnification 1200X. Corrosion-Fatigue Striations

definite striations found on any sample at any stress level under any condition.

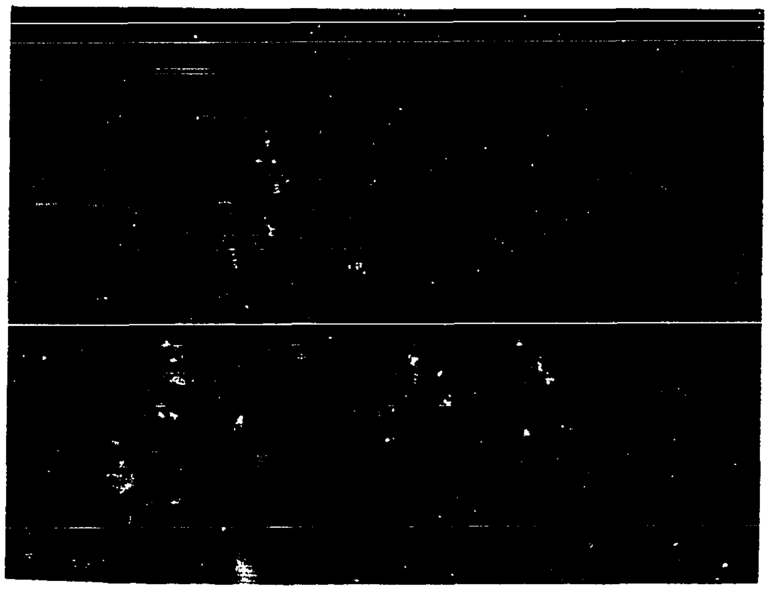
Corrosion-Fatigue, Three Hour Series

The three hour corrosion-fatigue series yielded just one area of reasonably well defined marks shown in Figure 32. This area was on Specimen No. 231 and came from a point near the edge of the fracture surface where normally the striations would be completely obliterated.

Corrosion-Fatigue, One-Half Hour Series

The one-half hour corrosion-fatigue series also yielded only one area of interest. It appeared on Specimen No. 334 and is shown in Figure 33. If compared with Figure 29, one might assume that this was near the edge of the corrosion-fatigue area close to the tensile failure. This is indeed the case. The lower right hand area in the photomicrograph is part of the tensile portion of the failure; the corrosion-fatigue area takes up the rest of the photograph.

What appeared to be cracks were found in some areas on both the fatigue and corrosion-fatigue samples. One of these areas, on Sample No. 334, is shown in Figure 34. This microcracking, if indeed it is cracking, is not confined to any particular portion of the fracture surface, it is found near the edge in some samples and in the interior of others.



33. Specimen No. 334. Magnification 500X. Line of Demarcation Between Corrosion-Fatigue and Tensile Failure Area

Figure 34. Specimen No. 334. Magnification 500X. Suggestion of Specimen Microcracking

Microscopic Examination, Rotating Bending Specimen Cross Sections

The rotating beam specimens were mounted for metallographic examination so that longitudinal sections were examined which went through areas of interest. These areas included fatigued and corrosion-fatigued areas of fracture surfaces and secondary cracks which could be seen on the specimen surface. The specimens were examined and photographs were made in the unetched condition to be certain that any fine detail would not be masked by the etching process.

Dry Fatigue, Six and Three Hour Series

The six hour fatigue series was typical of what fatigue samples are customarily supposed to look like in cross section. Examination of Specimen No. 103 revealed no cracks along the edges examined. No pitting or intergranular corrosion was evident. Away from the single fatigue crack which caused failure, the sample could be considered a completely normal piece of 2024-T4 aluminum alloy. The second specimen in this series was also normal in appearance. The last of this series, Specimen No. 503, was the only one that might be considered to have departed from the norm. Here, evidence of very slight pitting was seen on the surface. However, since the surface had an "orange peel" appearance due to the tensile testing, it is possible that the slight depressions seen were caused by localized surface yielding and not due to any corrosion mechanism. The three hour fatigue series specimens were normal except for some slight pitting on Specimen No. 110.

Dry Fatigue, One-Half Hour Series

Figures 35 and 36 are examples of the type of cracking which occurred on the one-half hour series of fatigue samples. This is a major departure from the previous behavior, and it occurred on all of the four samples which comprise this group. The cross-section of Specimen No. 28, the first of this series, showed a total of ten cracks in the area examined. The cracking typical of this series is that shown in Figures 35 and 36. These were taken from opposite sides of Specimen No. 529. Note in Figure 35 the large crack adjacent to the fatigue crack itself, which is the right hand edge of the photomicrograph. Two small cracks can just be seen between the two large ones. Figure 36 shows the opposite side of this same specimen, not too far removed from the main fracture. The size and spacing of these five cracks seems to have no particular relation to stress pattern set up during the fatigue test. This statement can be made about all of the samples in this group. Also, as the figures indicate, the cracks were generally transgranular and perpendicular to the applied stress. No definite intergranular corrosion was found on any of the rotating beam fatigue cross-sections examined.

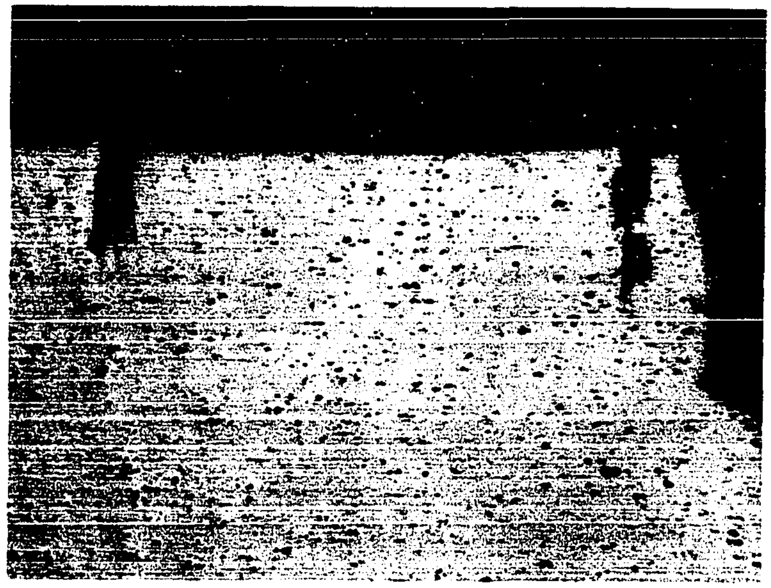


Figure 35. Specimen No. 529. Magnification 65X. Surface Cracking Near Fatigue Area

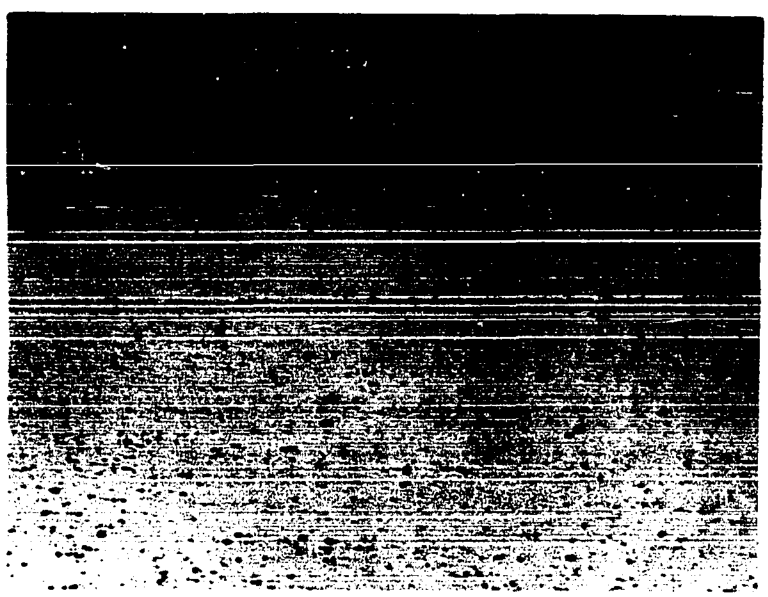


Figure 36. Specimen No. 529. Magnification 65X. Surface Cracking

Corrosion-Fatigue, Six Hour Series

Microscopic examination of the corrosion-fatigue cross-sections always revealed cracks, intergranular corrosion, or a combination of both. Some unusual cracking was also in evidence. An example of this unusual cracking showed up on the first member of the six hour corrosion-fatigue series, Specimen No. 713. Figure 37 is an example of pure fatigue cracking. The path of the crack into the body of the specimen is almost a straight line. Nearby, on the same side of the same specimen, was the combination of transgranular and intergranular cracking shown in Figure 38. This specimen had a large amount of minor pitting and intergranular corrosion along its surface, as for example the patch to the right of the crack in Figure 37.

The specimens in this series exhibited much of the same type of cracking which was seen in the one-half hour fatigue tests. Figure 39, which was taken on Specimen No. 310, shows three cracks that could just as well have come from the fatigue series. Oddly enough, these three cracks were the only ones on this specimen. The last two specimens examined were liberally sprinkled with intergranular corrosion, small cracks, or combinations of the two effects.

Corrosion-Fatigue, Three Hour Series

The three hour corrosion-fatigue series was characterized by extensive but separate patches of intergranular corrosion along the edges examined. Sometimes these patches

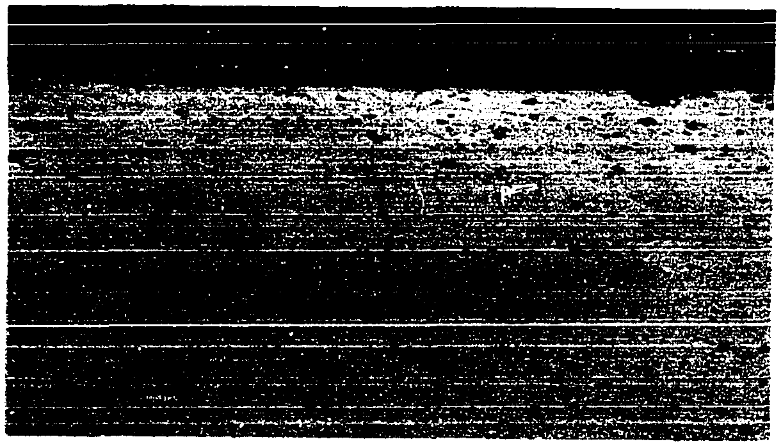


Figure 37. Specimen No. 713. Magnification 125X. Faint Transgranular Cracking

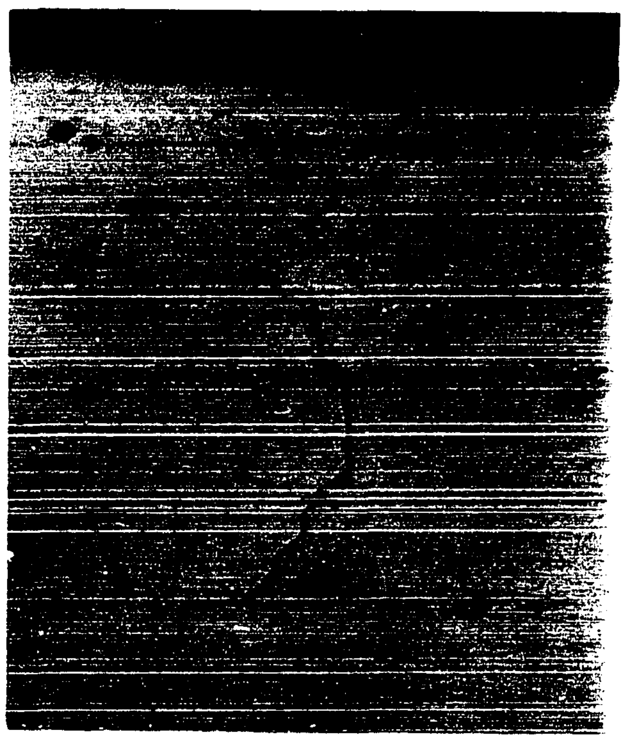


Figure 38. Specimen No. 713. Magnification 500X. Combination Transgranular and Intergranular Cracking

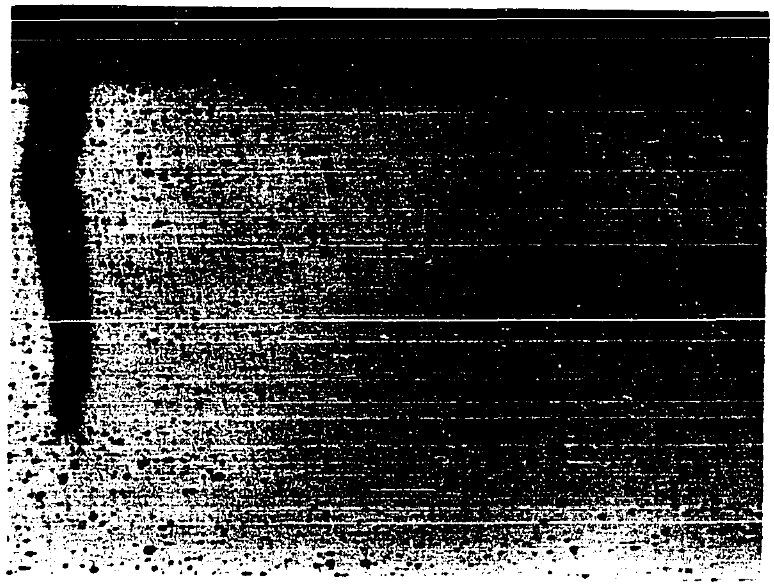


Figure 39. Specimen No. 310. Magnification 65X. Corrosion-Fatigue Surface Cracking

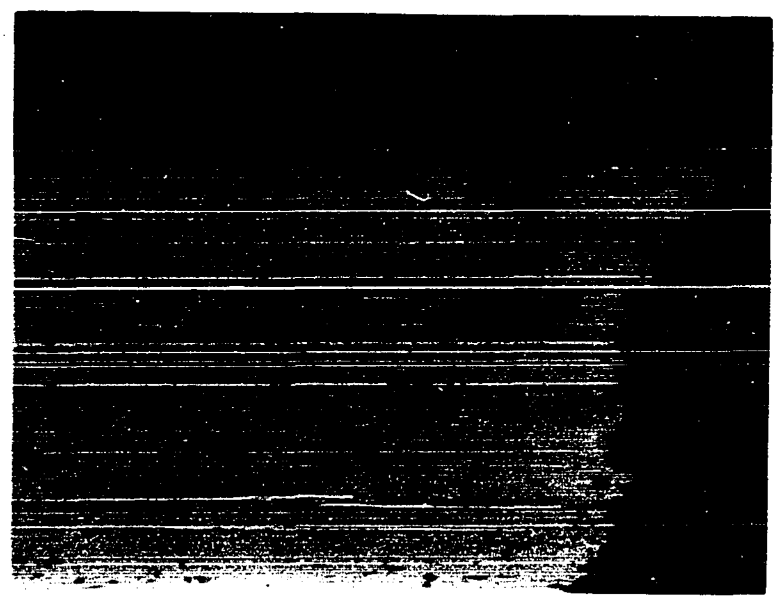


Figure 40. Specimen No. 10. Magnification 125X. Intergranular Corrosion Near Fatigue Surface

looked like enlarged pits as shown in Figure 40. This photomicrograph also indicates that the tensile failure in this plane went through a similar area of corrosion. In some instances, the intergranular corrosion occurred in conjunction with the corrosion-fatigue cracking as shown in some of the faint patches in Figure 41. It is this type of fine detail that etching would tend to mask and at worst completely destroy. Though faint, this type of intergranular corrosion was found on all of the specimens of the three hour series.

Corrosion-Fatigue, One-Half Hour Series

The one-half hour series of corrosion-fatigue tests departed from the two previous corrosion-fatigue series, in the same manner as did the one-half hour fatigue series depart from the two longer fatigue series. The first specimen of this group, No. 334 was a reasonably typical corrosion-fatigue specimen; intergranular corrosion and corrosion-fatigue cracking were found on both sides examined. One large crack is shown in Figure 42. This crack compares favorably with that shown in Figure 38. In the next specimen in this group, No. 832, intergranular corrosion is very limited in extent and corrosion-fatigue cracking is the predominant feature. With the last specimen, No. 332, the intergranular corrosion disappears completely. The corrosion-fatigue cracking that does occur is indistinguishable from that seen on any of the fatigue specimens. Figure 43 shows

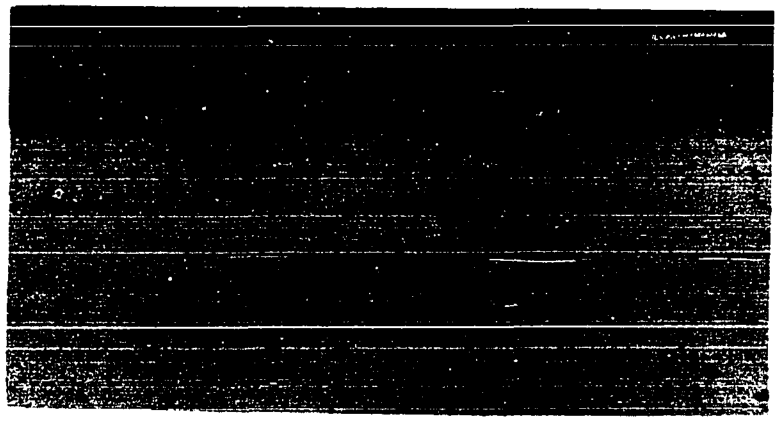


Figure 41. Specimen No. 327. Magnification 125X. Intergranular Type Damage

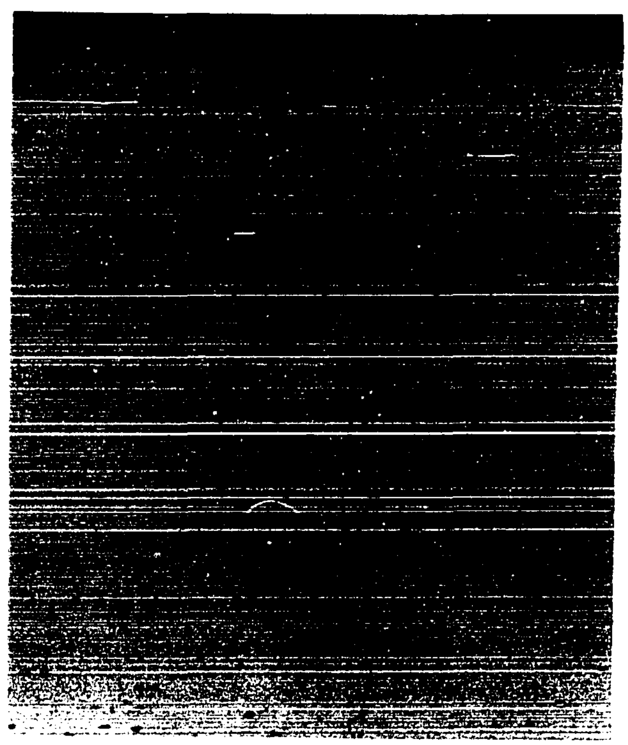


Figure 42. Specimen No. 334. Magnification 125X. Transgranular Corrosion-Fatigue Cracking

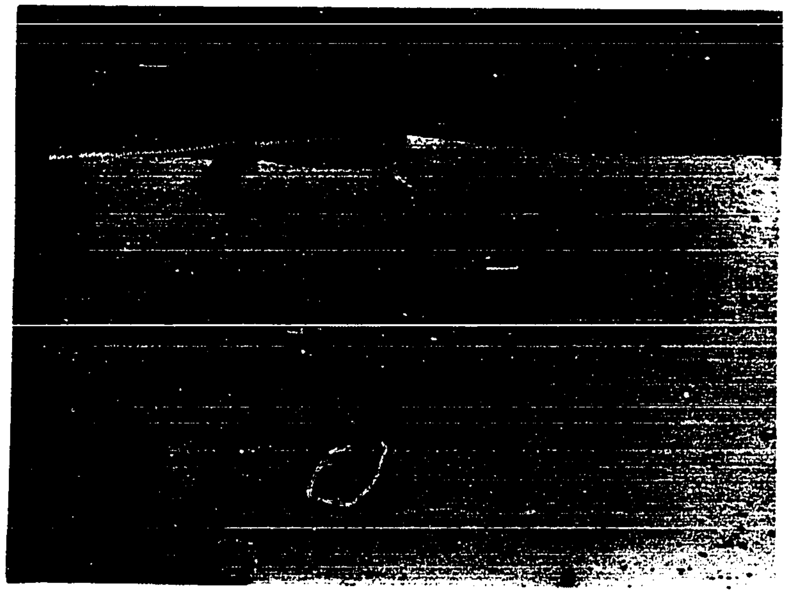


Figure 43. Specimen No. 332. Magnification 125X. Corrosion-Fatigue Cracking Near Fracture

the appearance of two of the cracks on Specimen No. 332 near the tensile failure. Compare this with the fatigue cracking shown in Figure 35.

Table VII is a summary of the observations made on

TABLE VII

ROTATING BENDING SAMPLE DEFECTS
NUMBER OF DEFECTS APPEARING ON CROSS SECTIONS EXAMINED

Testing Time	Number of Cracks	Cracks Plus Intergranular Corrosion	Pits Plus Intergranular Corrosion
Fatigue Samples			
6 hour series	0	0	0
3 hour series	0	0	0
1/2 hour series--30 min.	10	0	0
25 min.	4	0	0
20 min.	13	0	0
15 min.	3	0	0
Corrosion-Fatigue Samples			
6 hour series--6 hr.	1	1	2
5 1/2 hr.	2	1	8
5 hr.	1	5	10
4 1/2 hr.	0	2	4
4 hr.	1	0	5
3 hour series--3 hr.	0	2	19 (a)
2 1/2 hr.	1	6	17 (a)
2 hr.	3	6	4
1 1/2 hr.	2	10	8
1 hr.	0	17	5
1/2 hour series--30 min.	3	5	0
25 min.	5	8	1
20 min.	3	0	0

(a) Practically continuous intergranular corrosion on surface.

specimen cross-sections of samples tested in rotating bending. The term crack is taken to mean those surface defects which are mainly transgranular and perpendicular to the surface and are similar to those shown in Figures 35 and 36. In the examination of the corrosion-fatigue specimens, cracks were often associated with intergranular corrosion and are so listed. Isolated pits or intergranular corrosion without any noticable cracking are listed separately.

Plate Flexure Tests

Table VIII lists the results of the plate flexure tests in both fatigue and corrosion-fatigue. The fatigue values in all cases are below the fatigue scatter band for this alloy shown in Figure 9. This fatigue band, however, was determined by using cylindrical specimens in an R. R. Moore type test and is not directly applicable to the plate specimens used here. No similar fatigue band has been published for plate flexure tests.

The fatigue fractured plate samples were cross-sectioned as shown in Figure 6 and examined for the presence of secondary cracks. Secondary cracks are those which are initiated in the fatigue process but are not associated with the critical crack which causes failure. The cross-sections were microscopically examined at 200 diameters. Figure 44 is a graphical representation of the number of secondary cracks found per unit length examined without regard to their orientation. Since the cross-sections were examined in both

TABLE VIII

PLATE FLEXURE TEST RESULTS

Spec. No.	Freq. C.P.M.	Max. Fiber Stress, psi.	No. of Cycles to Failure	Duration of Test, hours
		Fatigue-Tested Under Atmospheric Conditions		
1	1,200	35,000	54,100	0.75
2	1,200	35,000	79,200	1.10
3	1,200	22,000	331,300	4.60
4	1,200	22,000	551,500	7.67
5	1,200	17,000	5,176,000	71.88
6	1,200	17,000	3,680,000	51.11
7	1,900	35,000	74,100	0.74
8	1,900	35,000	60,600	0.58
9	1,900	22,000	330,600	3.18
10	1,900	22,000	671,000	6.45
11	1,900	17,000	9,123,000	87.72
12	1,900	17,000	5,679,000	54.61
		Corrosion-Fatigue - 3% NaCl Solution		
13	1,200	31,000	31,400	0.44
14	1,200	31,000	44,400	0.62
15	1,200	14,000	800,000	11.10
16	1,200	14,000	567,000	7.87
17	1,200	7,000	5,160,000	71.70
18	1,200	7,000	3,630,000	50.40
19	1,900	31,000	52,800	0.46
20	1,900	31,000	51,000	0.45
21	1,900	14,000	918,000	8.05
22	1,900	14,000	616,500	5.41
23	1,900	7,000	6,692,000	58.72
24	1,900	7,000	5,650,000	49.55

a longitudinal and transverse direction, this breakdown is presented for the corrosion-fatigue specimens in Figure 45.

The large number of cracks seen were placed into one of four broad classifications:

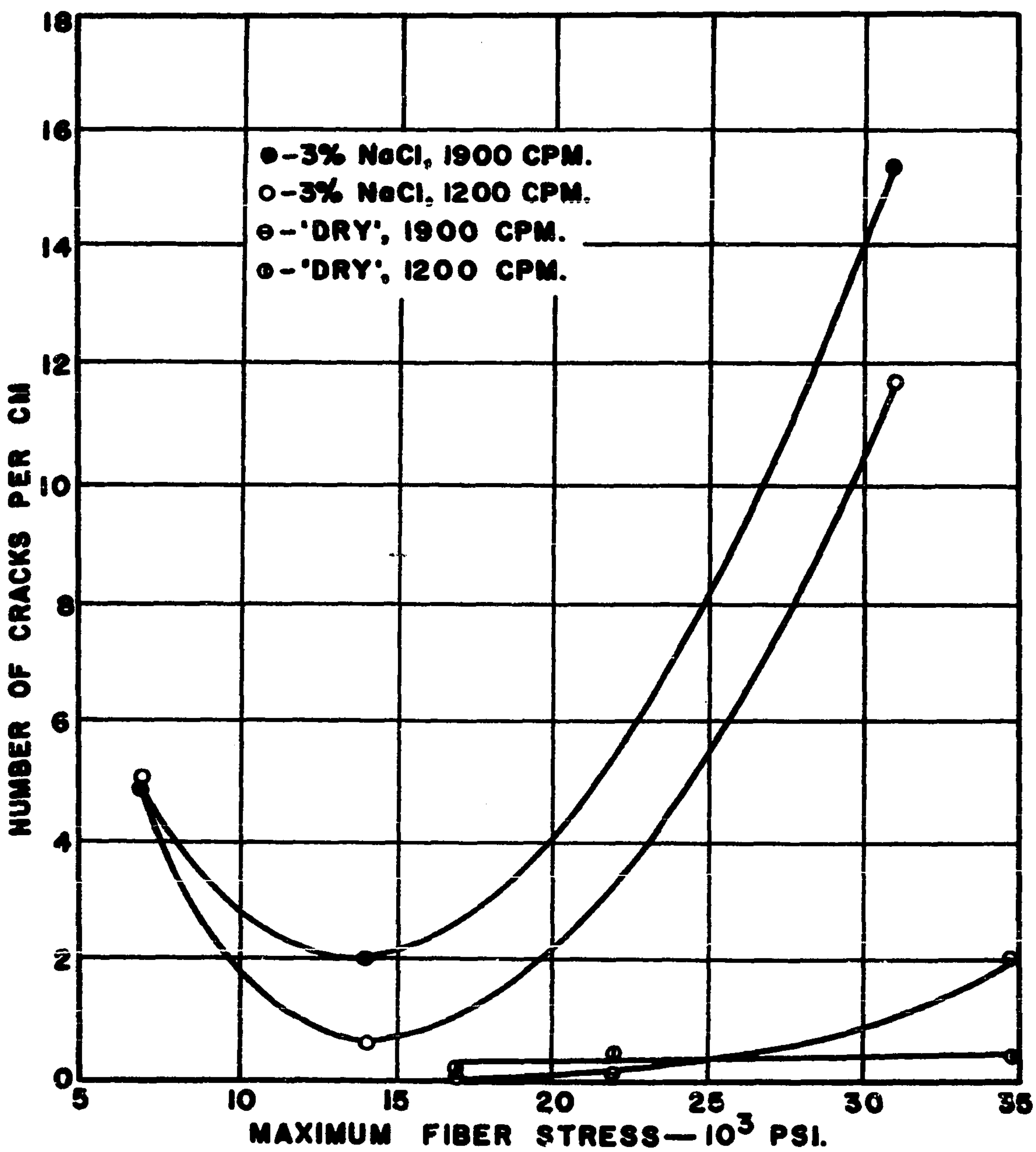


Figure 44. Plate Flexure Tests, Number of Cracks per Unit Surface Distance Versus Maximum Fiber Stress

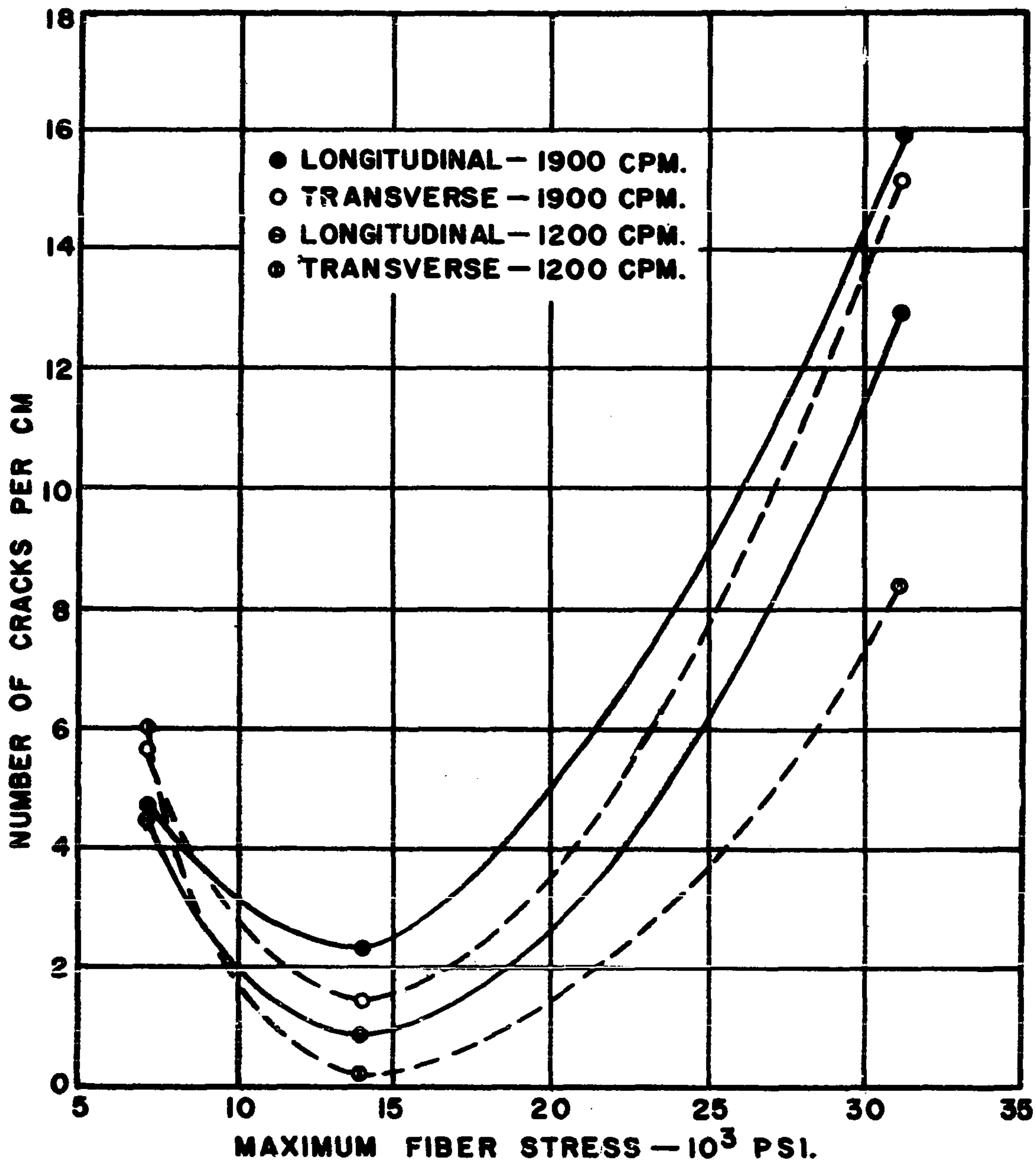


Figure 45. Plate Flexure Corrosion-Fatigue, 3% NaCl Solution. Number of Cracks in the Longitudinal and Transverse Directions Versus the Maximum Fiber Stress

Group 1 - Transgranular cracks which are usually associated with "dry" fatigue.

Group 2 - Transgranular corrosion-fatigue cracks.

Group 3 - Intergranular corrosion-fatigue cracks.

Group 4 - Extended intergranular damage over the surface of the specimen, blisters, exfoliations, and deep and narrow surface pits.

It was not always possible to place a defect uniquely into only one of these groups. If a crack represented a border line case between a transgranular "dry" and a transgranular corrosion-fatigue crack, it was counted in both groups 1 and 2. Similarly, some cracks were counted in both groups 2 and 3. These were transgranular corrosion-fatigue cracks which initiated from previously established corrosion-fatigue damage of an intergranular nature adjacent to the surface. Figures 46 through 49 present defects typical of the four groups.

Figure 50 presents a summary of the types of defects found versus the maximum fiber stress for a testing speed of 1,200 cpm. Similar information for a testing speed of 1,900 cpm is presented in Figure 51. A further breakdown of the corrosion-fatigue defects which presents the ratios of the intergranular and parallel-with-surface cracking to transgranular and perpendicular-to-surface cracking versus the maximum fiber stress is shown in Figure 52.

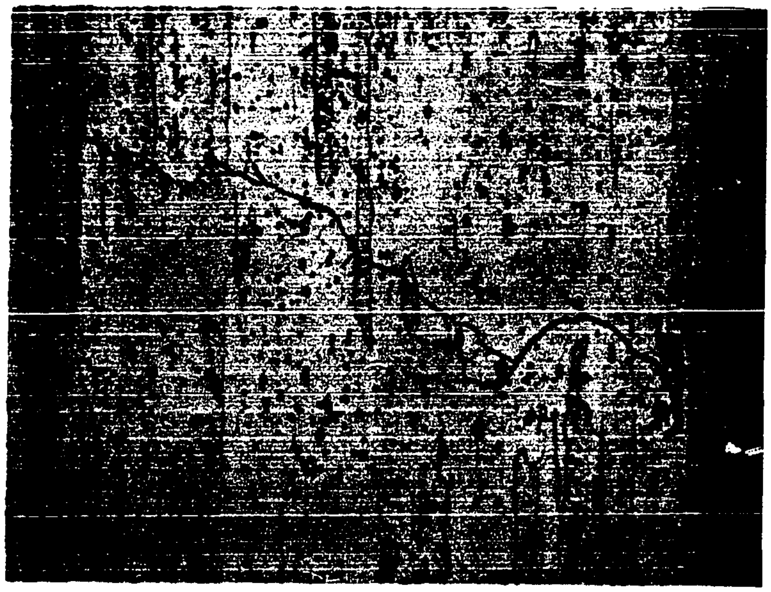


Figure 46. Specimen No. 8S. Magnification 120X. Typical Example of Group 1 Damage

Figure 47. Specimen No. 19E. Magnification 200X. Typical Example of Group 2 Damage

Figure 48. Specimen No. 24E. Magnification 300X.
Typical Example of Group 3 Damage

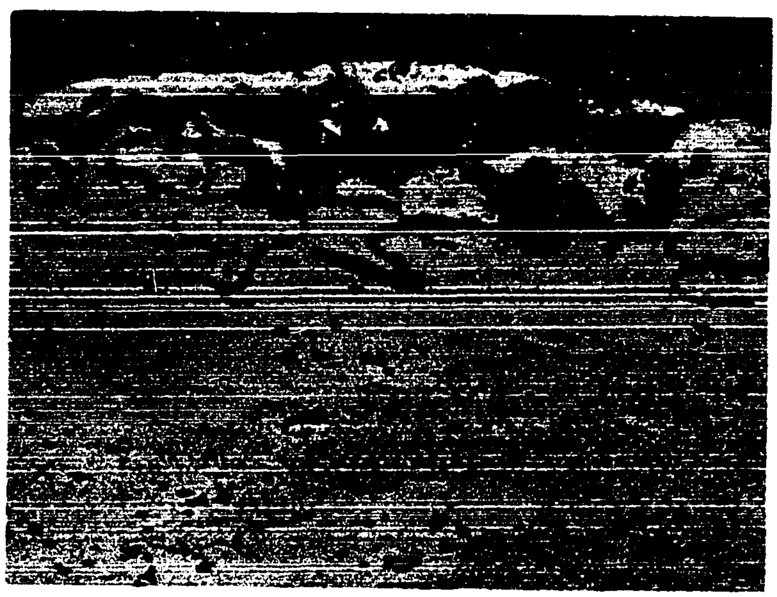


Figure 49. Specimen No. 32E. Magnification 350X.
Typical Example of Group 4 Damage

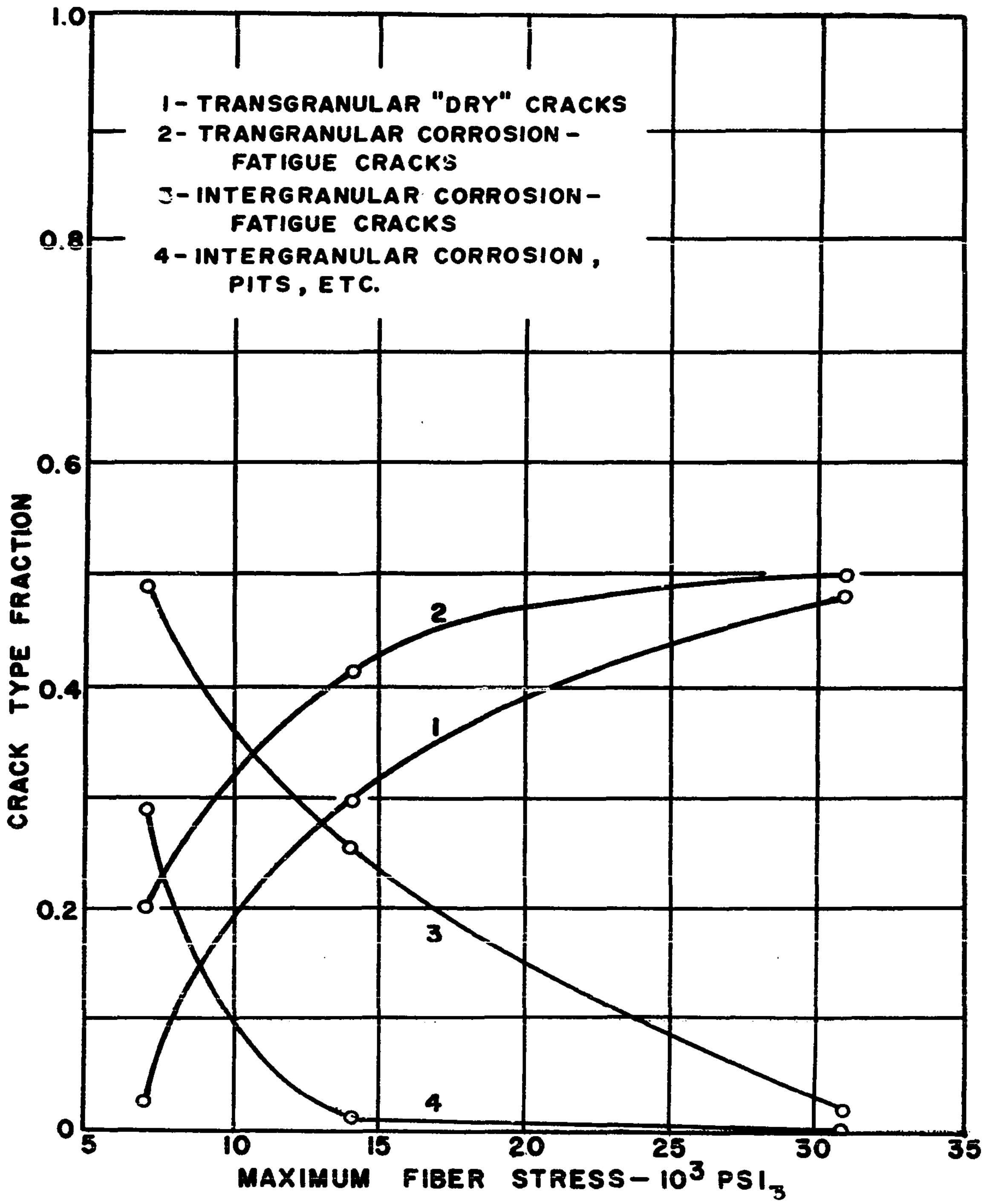


Figure 50. Plate Flexure Corrosion-Fatigue, 3% NaCl Solution, 1200 CPM
Crack Type Fraction versus Maximum Fiber Stress

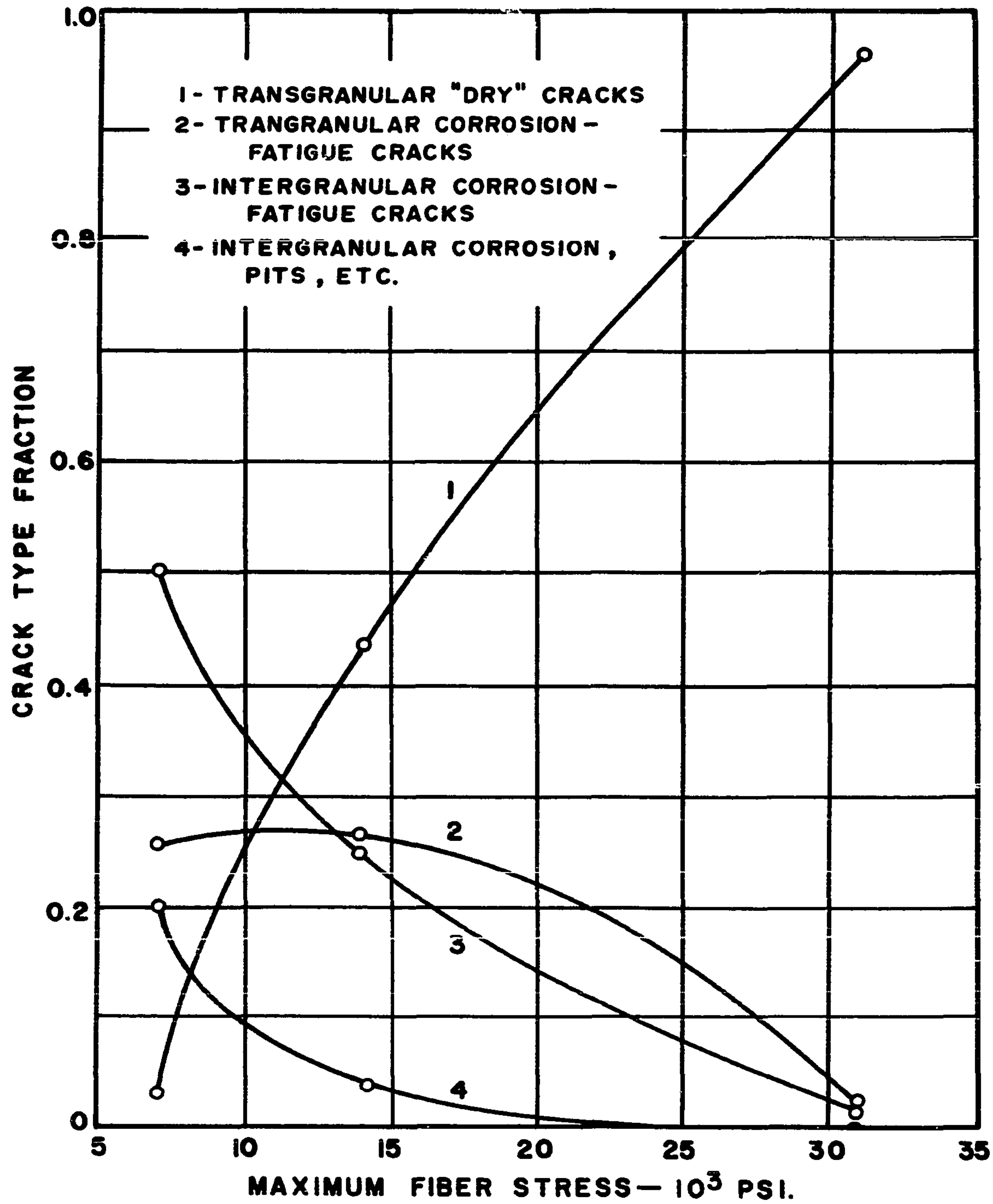


Figure 51. Plate Flexure Corrosion-Fatigue, 3% NaCl Solution, 1900 CPM Crack Type Fraction versus Maximum Fiber Stress

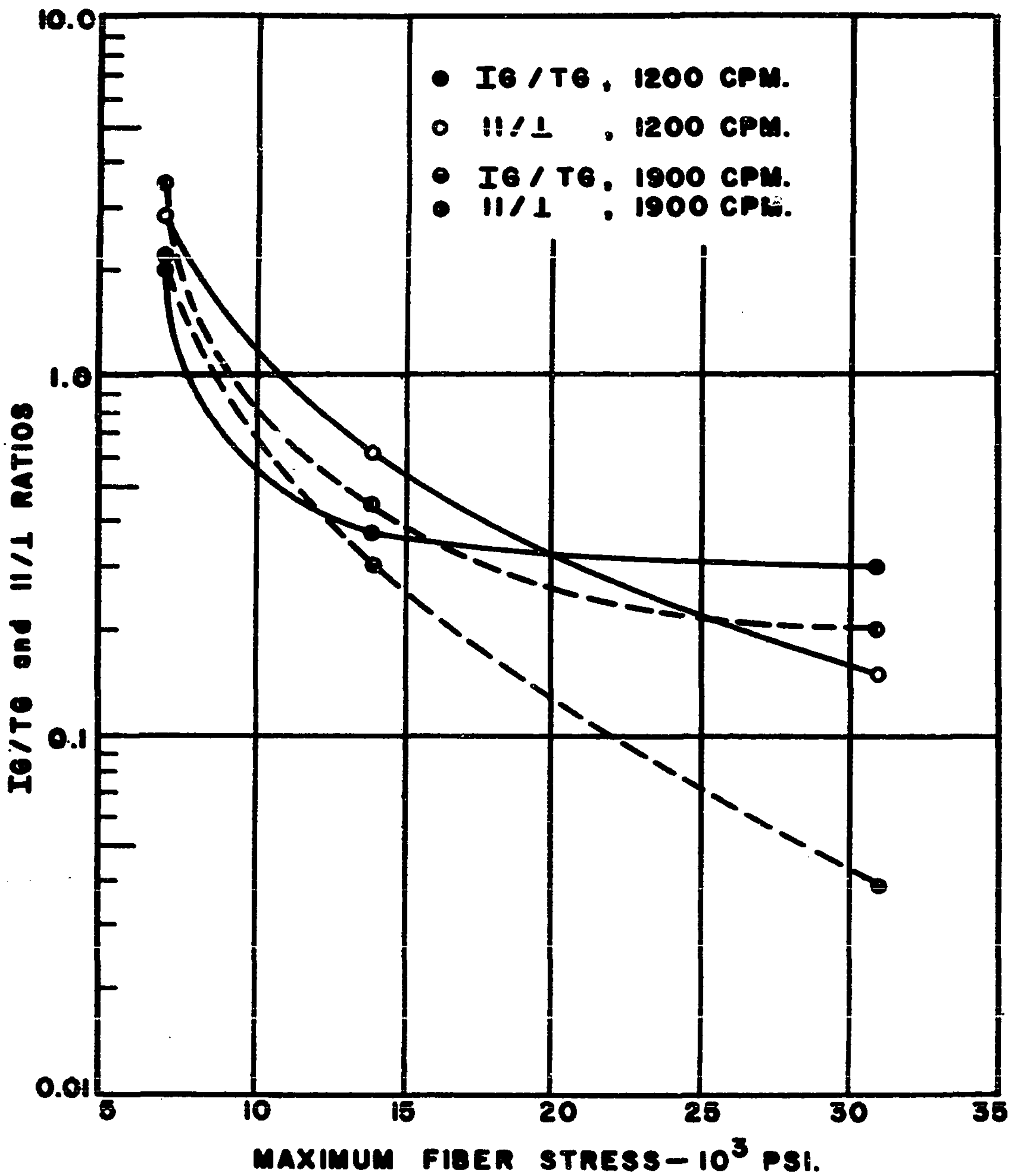


Figure 52. Plate Flexure Corrosion-Fatigue, 3% NaCl Solution, Ratios of Intergranular and Parallel-With-Surface Cracking to Transgranular and Perpendicular-To-Surface Cracking Versus Maximum Fiber Stress

CHAPTER IV

DISCUSSION OF RESULTS

The results obtained in rotating beam tests are discussed separately from those of the plate flexure tests. Because of the difference in experimental conditions in the two tests, the results cannot be directly compared.

Some explanation for the difference in salt concentration of the solutions used in the two different tests is in order. In the plate flexure tests, the speed of testing was limited by the design of the machine. This factor in turn lengthened the time of testing considerably. Since an increase in salt concentration was probable during the longer tests, the effect of this increase was minimized by the use of a high initial salt concentration. As Figure 7 shows, the greatest percentage decrease in fatigue properties for this alloy occurs for the application of the aqueous environment. Addition of salt to the water further reduces fatigue life, but salt concentrations above three percent do not cause a proportionate decrease in the properties of the alloy. From this observation it can be inferred that the increase in salt concentration which occurred with time in the plate flexure tests did not alter the corrosion-fatigue characteristics obtained to any appreciable extent. Figure 7 indicates that if a lower initial salt concentration had been used, this might not have been the case.

In the rotating beam tests, the physical arrangement of the tests precluded any salt concentration build-up since the test section of the corrosion-fatigue sample was never allowed to dry during the test. Here, a much lower salt concentration, 0.5 per cent, could be used for the dual purpose of providing a major change in the test results when compared with the fatigue tests and yet not corroding the surface to such an extent that gainful visual examination would be impaired.

Rotating Beam Results

Both the tensile and fatigue tests on the bar stock resulted in values considered normal for 2024-T4 aluminum alloy. For the corrosion-fatigue tests, however, e.g., the S-N curve shown in Figure 9, it is not possible to ascribe a "normal" behavior. There are only isolated examples in the literature of the behavior of materials in specified corrosive media. The Corrosion Handbook (51) summarizes some of the early work of McAdam and reports the following values for Duralumin, an early name for 2024 aluminum alloy. All of these tests were conducted at a speed of 1450 cycles per minute and all of the values shown are for failure in 10^8 cycles.

Condition	Tensile Strength psi.	Endurance Limit psi.	Corrosion-Fatigue Limits Well Water psi.	Corrosion-Fatigue Limits Salt Water psi.
Hardened	69,100	17,000	7,700	6,500
Annealed	33,400	13,500	7,500	6,700

Little data such as this can be found in the literature. Yet even these results cannot be directly compared with those obtained in this investigation. McAdam used a testing speed less than half of that used here and his salt solution was far more concentrated.

There are two ways, both having equal merit, of interpreting the differences seen between the fatigue and corrosion-fatigue curves in Figure 10. If a particular stress is most important, such as 25,000 psi., the life reduction due to the corrosion-fatigue drops from a value in excess of 10^7 cycles to slightly over 1.5×10^5 cycles, almost two orders of magnitude. On the other hand, if the life of a unit is known, this might be the more important factor. The figure shows that for a life of 10^6 cycles the reduction would be from approximately 28,000 psi. in fatigue to less than 15,000 psi. in corrosion-fatigue or about a factor of one-half. Regardless of the interpretation, the reduction due to corrosion-fatigue is severe, either in the cycles to failure at a given stress or the stress supportable for a given life.

The six, three, and one-half hour fatigue and corrosion-fatigue tests were designed to give three pairs of samples of approximately the same life span in cycles. Since all of the tests were run at the same cyclic speed, each pair was subjected to its respective atmosphere for an equal time. This meant that the three stresses used for the fatigue tests could not be the same as those used for the corresponding corrosion-fatigue tests. For example, a maximum fiber stress of approximately 32,000 psi was used in the three hour fatigue tests. In corrosion-fatigue, the three hour stress drops to approximately 17,000 psi. It is not possible to keep constant the three variables time, stress and cycles to failure when comparing fatigue with corrosion-fatigue data. A valid case can be made for either of the above interpretations. In this investigation, time of testing was considered paramount and, since the speed of testing was also held constant, the test stresses had to be varied.

Fatigue Tests

Microexamination of the specimen surfaces and cross-sectional areas of the six hour series of fatigue samples revealed normal fatigue damage. Deviation from normal or customary behavior started with the three hour fatigue series. Here, the fracture surface exhibited multiple level cracking and the specimens contained secondary fatigue cracks away from the fracture surface. None of these secondary cracks appeared on the cross-sections from this series that were examined metallographically. This is believed due to the small probability of the section examined passing through one or more of the small number of defects present.

Examination of the one-half hour fatigue samples revealed numerous cracks away from the central portion of the samples. These secondary cracks were present on all four samples of this series. While most of the secondary cracking occurred on the specimen run to failure, it was also apparent on the sample run to only one-half of its expected fatigue life. This is not confirmed by the crack count seen in Table VII, it must be remembered that the table is based on only one cross-section with the probability of intersecting secondary cracks mentioned previously.

Table VII seems to indicate that crack density decreases with longer testing times. This is not the case. The shorter the testing time in any series, the greater the residual tensile strength of the specimen. Thus, when tensile tested, the higher the residual tensile strength the greater the tensile strain at fracture on the surface of the specimen. The higher this strain, the smaller the crack that will be "opened" to the extent that it can be seen at a low magnification. Conversely, when a specimen has been fatigued to the point where its cross-section is no longer able to support a high tensile load, the longitudinal tensile strain at the surface at fracture will be small. Under this condition, small cracks may stay closed and will not be noted.

The loading conditions of the rotating beam machine were a factor promoting multiple cracking. This fatigue machine is a constant load device. The formation of the first fatigue crack does not relieve the longitudinal fiber stresses in the sample outside of the immediate area of the crack. The load on the specimen does not change and the presence of a crack, reducing the specimen cross sectional area, would cause the constant load to bend the specimen to an even greater extent than if the crack were not present. In a constant deflection machine as was used in the plate flexure tests, the maximum fiber stress must be reduced to a greater extent in the area of a fatigue crack.

Corrosion-Fatigue Tests

Microexamination of the corrosion-fatigue specimens revealed that they usually contained, as expected, more than one crack. In the literature, as for example in Gilbert (52), it is stated that this multiple cracking is a characteristic feature of corrosion-fatigue. This statement was confirmed by the rotating beam tests. All of the corrosion-fatigue specimens did indeed exhibit multiple cracking. However, both the one-half and three hour fatigue specimens also contained multiple cracking.

Table VII indicates that a much more characteristic feature of corrosion-fatigue, at least in this alloy, was the presence of intergranular corrosion or pitting on the specimen surface. The majority of the corrosion-fatigue samples examined revealed a combination of three effects--pitting, intergranular corrosion and multiple secondary cracking. However, the statement cannot be made that all corrosion-fatigue specimens will contain all three defects. One corrosion-fatigue specimen did not contain any intergranular corrosion, did not pit, but did exhibit multiple level cracking. This specific one-half hour series corrosion-fatigue specimen, Number 332, could not be distinguished by any test made here from the one-half hour fatigue samples. These facts lead to the conclusion that it is not always possible to distinguish between fatigue and corrosion-fatigue fractures.

Specimen 332 was the third sample in the one-half hour corrosion-fatigue series. The sample was subjected to approximately twenty minutes exposure to the salt solution. The surface of the specimen was barely discolored and this factor could not be used to differentiate it from a fatigue specimen. The next specimen in this group, one that was subjected to the corrosive medium for 25 minutes, does show a reasonably well defined discoloration due to surface corrosion and the line of demarcation where the rubber seal seated on the specimen can be seen. Even without any other examination, this discoloration would indicate a corrosion-fatigue situation. Results obtained with Specimen Number 332, however, indicate that it is possible for a corrosion-fatigue specimen tested under a comparatively high stress at the speed of testing used here, to be visually and microscopically indistinguishable from a fatigue sample tested at a much higher stress necessary to give a comparable life.

An explanation of these findings lies in the time dependence for both intergranular corrosion and pitting. Under the stress and corrosive conditions to which Specimen Number 332 was subjected, twenty minutes was not sufficient time for these defects to develop to an extent that they were visible. The cracking was mainly or entirely fatigue in outward appearance.

The surface defects associated with the corrosion-fatigue bore no apparent relationship to the applied stress on the samples. In Figure 43, the small crack is nearest the fracture, the larger crack further away. In another specimen, a small crack had two larger cracks on either side of it. The stress concentration factor of the specimen was too mild to cause a gradient in the defects seen. Pitting, intergranular corrosion and cracking occurred over approximately a one-half inch length of the corrosion-fatigue specimens.

If the spacing of striations is to be used as a measure of crack propagation, one must accept the view of Forsyth (53) that one striation is produced during one cycle of stress. These striations are produced at the crack front as it proceeds into the specimen. The fineness of this detail is apparent in Figures 26 and 31. The parallel markings in the first figure are approximately 15×10^{-6} inches apart and in the second figure the value is 80×10^{-6} inches apart. These striations come from two different specimens, one a fatigue sample with an expected life of six hours, the other a corrosion-fatigue sample with the same expected life. Yet the corrosion-fatigue specimen, with an initial load of 14,700 psi., showed the wider striations by a factor of about five than the fatigue specimen with an initial load of 23,700 psi. Without the knowledge as to the specific time of the creation of a particular area of striations, or of the local stresses that caused them, attempts to determine the gross crack propagation rates for rotating beam specimens by the use of striations is illusionary.

The frequency of defects in the fatigue samples as reported in Table VII does not agree with Gough (54) who states that secondary cracking is minor in fatigue testing. A fatigue test is usually run until the specimen fails, and no examination is made to check for secondary cracking. In this investigation, all of the specimens were tensile tested after fatigue testing and were subjected to varying degrees of tensile strain. This procedure actually helped to delineate cracks. When a sample was tested to only a portion of its expected fatigue life and only small cracks might be present, the high tensile strength remaining resulted in a large tensile strain helping to open these tiny cracks and make them more observable. This testing procedure also accounts for the fact that the crack density seems to increase as the residual tensile strength increases. Figure 37 would be considered a normal appearing crack before tensile testing and Figure 39 shows a typical crack that had been opened up during tensile testing due to localized yielding. Figure 39 is the most typical for the cracks reported in Table VII that were made more visible by tensile testing.

The results of the rotating beam tests can be summarized as follows. In fatigue tests at the lowest stress the specimens behaved in what might be termed a normal manner. That is, the alternating stresses ultimately produced a crack which grew until a sufficient proportion of the specimen cross-section was included to result in the failure of the specimen. The energy input of this alternating stress was insufficient to form more than one crack but was absorbed in enlarging the one that first formed. At the intermediate fatigue stress, this was no longer the case since multiple surface cracking was evident. At this stress the crack resistant quality noted in the lowest stress tests was overcome by the higher applied stress and the formation of the first crack did not preclude the formation of others. Multiple surface cracking was even more evident in the highest stress fatigue tests. Here, a large number of surface cracks were seen after only one-half of the expected fatigue life of the samples. No intergranular corrosion, pitting or other surface defects were noted on any of the fatigue samples.

In the corrosion-fatigue tests, multiple surface cracking was evident in all of the samples. Intergranular corrosion and pitting were common. In terms of gross numbers, the longest exposure to the corrosive medium did not necessarily result in the greatest tendency for surface cracking. The samples at the intermediate stress, on the basis of the count taken here, exhibited more surface cracking and intergranular corrosion than did the lowest stress long time samples. The samples run at the highest stress included one which did not exhibit any corrosion effects whatever yet did contain multiple surface cracking.

These results indicate that, under the test conditions used, the normal crack resistance of this alloy is reduced by the presence of the corrosion medium. In all three of the corrosion-fatigue series the stresses used were below the lowest of the fatigue stresses. The presence of the corrosion medium must facilitate the formation of crack sites at lower applied stresses. Thus the mechanism of corrosion-fatigue is different from that of simple fatigue primarily in lowering the applied stress necessary to produce cracks. This is seen notably in one of the high stress corrosion-fatigue tests. No corrosion effects were seen on this sample. Yet it showed multiple cracking at a stress which, if used in simple fatigue, would not have shown this effect.

Plate Flexure Results

Figure 44 summarizes the crack frequency determined for all of the plate sample tests. The two curves for the fatigue or dry samples show a very low crack density averaging less than one crack per cm. In only one instance, the high stress 1,900 cpm. tests, did this average go above this figure to approximately two cracks per cm. Results shown in Table VIII do not indicate any consistent difference due to testing speed in the fatigue values obtained.

The corrosion-fatigue results shown in Figure 44 indicate that a much higher crack density was obtained than in the fatigue tests. This crack density is the greatest at the high stress, passes through a minimum for the intermediate stress and then increases as the stress is lowered further. Figure 44 also indicates that, except for the lowest stress, the crack density was somewhat higher for the 1,900 cpm. testing speed than for the 1,200 cpm. testing speed. Thus testing speed appears to have a small but measurable effect on the crack density.

As presented in Table VIII, for each corrosion-fatigue specimen of a given life at 1,200 cpm., there is a corresponding one with a longer life at 1,900 cpm., each tested at the same stress level. These results are consistent with the picture presented by Lorkovic, Varallyay and Daniels (55) that the corrosion-fatigue life of a specimen, in cycles-to-failure, will increase as the testing speed is increased. However, it should be noted that, except for Specimen Number 13, each of the samples tested at 1,200 cpm. remained longer under test than did its mate tested at the higher speed. For example; Specimen Number 14 had a life of 44,400 cycles during its test about 37 minutes. At the higher speed, Specimen Number 20 had a life of 51,000 cycles but its test took only 28 minutes, approximately 25 per cent less time of exposure to the salt solution.

As drawn in Figure 44, the corrosion fatigue curves are shown to have their minimum values at the intermediate stress of 14,000 psi. The minimum in the curves might have been shifted one way or the other if more samples had been tested at stresses both slightly above and below this value of stress.

Figures 50 and 51 are plots of the four individual crack types as defined on page 100. Both figures show that, at the lowest stress, transgranular cracking is at a minimum and that the intergranular corrosion-fatigue cracking is at a maximum. The other forms of damage are intermediate in value. As the test stress is increased, for both testing speeds, the intergranular corrosion-fatigue cracking and other intergranular damage on the samples decreases to a minimum. At the highest stress, all of the intergranular damage, of whatever kind, drops to a total of only a few per cent of the total damage.

At both testing speeds, as the test stress is increased, there is a significant increase in the proportion of transgranular cracking. As shown in Figure 51, at the higher testing speed, over 95 per cent of the cracks at the high stress are transgranular "dry" type cracks. At the lower testing speed, these Group 1 type cracks increase up to almost 50 per cent of the damage at the highest stress. At this low speed, the transgranular corrosion-fatigue cracking increases up to 50 per cent. Thus, about 95 per cent of the cracks found at the high stress were transgranular in nature. At the high speed they are all similar to "dry" fatigue cracks. At the lower speed, half of the cracks are similar to "dry" cracking and half are similar to corrosion-fatigue cracking.

Note was kept during the crack counts not only as to the intergranular or transgranular nature of the surface damage but also its orientation with respect to the specimen surface. Figure 52 is a plot of these ratios. All of the curves follow the same trend. This is not unexpected in the light of the two previous figures. At the low stresses, all of the ratios are over 1 with intergranular and parallel-with-surface damage in the majority. As the stress is increased, and therefore the time of testing decreased, all of the ratios become less than 1 with transgranular and perpendicular-to-surface cracking now in the majority.

In summary, for the plate flexure tests in corrosion-fatigue, the highest stressed samples produced the highest crack density. The higher testing speed produced more cracks than did the lower testing speed. About 95 per cent of the cracks seen were transgranular "dry" fatigue types.

As the test stress is lowered to the intermediate value there is a significant decrease in the density of cracks from an approximate value of 13 to less than 2 cracks per cm. The higher speed still produced the higher density of cracking. The surface damage seen was a mixture of crack types with a definite decrease in the transgranular cracking and a corresponding increase in the percentage of intergranular damage.

At the lowest stress, there is an increase in the crack density over that of the intermediate stress, although not to a value near that of the high stress. This was the only case in which there appeared to be no difference in the crack density due to the testing speed.

Most of these corrosion-fatigue results appear to be explainable in terms of the test conditions, i.e., stress and environment plus that important variable, the time the specimen was under test. Among the high strength aluminum alloys, 2024-T4 is noted for its crack resistant qualities. If the intermediate stressed samples, with their low crack density, are taken as a measure of this quality, the increase in crack density at the other stresses can be rationalized.

As the stress was lowered from the intermediate value, the time of the test increased accordingly. The samples were subjected to the salt solution for a longer time resulting in a large increase in intergranular damage. The cyclic stress was able to extend this damage into cracks. At the highest test stress, the time of testing was much reduced over that of the intermediate stress. However, the higher value of stress was now sufficient to promote the slightest pit or intergranular damage into a major transgranular crack.

The crack orientation can be explained on the basis of the time of testing. At the lowest stress, i.e., the longest time, the corrosion solution can cause much intergranular and parallel-with-surface damage. The high stress tests do not allow the time necessary for this type of damage and transgranular cracking predominates.

No direct comparison is possible between the plate flexure and the rotating beam corrosion-fatigue tests. In addition to the difference in specimen design and stressing conditions, the rotating beam samples were machined from extruded bar while the plate samples were machined from rolled plate. These differences are minor, however, against the differences in corrosion solution concentration and the differences in testing speed. It is interesting to note, in passing, that in the plate flexure tests, the intermediate test conditions produced the least cracking. In the rotating beam tests, although based on a limited count, the intermediate stress produced the most damage on the specimen surface.

A comparison of the fatigue results is possible, keeping in mind the difference in product and the manner of testing. In the fatigue tests the rotating beam samples exhibited a definite tendency for surface cracking as the test stress was increased. Based on the limited areas examined, this crack density was many times that found on any of the plate flexure fatigue samples. This comparison suggests that the type of fatigue test and the working of the alloy before test may have a larger effect on the test results than previously thought.

CHAPTER V

SUMMARY AND CONCLUSIONS

1. An aluminum alloy, 2024-T4 was tested in fatigue and corrosion-fatigue in both plate flexure and rotating bending. This research was conducted to study the crack morphology and the effect of the experimental variables on the cracking characteristics of the alloy.

2. Under rotating bending the tendency for multiple cracking increased with increasing stress level in fatigue; while multiple cracking occurred at all stress levels for failure in corrosion-fatigue even though these stresses were well below the stress required to initiate a single crack in fatigue. This corrosion-fatigue behavior is associated with extensive pitting and intergranular corrosion at the lowest stress levels (longest failure times) studied, but multiple cracking also occurs at the higher stress levels without apparent pitting or intergranular corrosion even though the stress level is lower than that which would cause multiple cracking in fatigue.

3. The tendency for multiple cracking at the higher stress levels in fatigue indicates that the initiation of the first crack does not reduce the surface stress below that

necessary for the initiation of secondary cracks. The constant load method of testing in rotating bending is a possible contributor to this phenomenon since the constant deflection plate flexure tests resulted in a much lower secondary crack density.

4. Fatigue and corrosion-fatigue striations were found on some specimen fracture surfaces. The compression cycle of the rotating bending tests tended to mask the striations by a grinding action. Those which were observed were extremely fine and followed no determinable pattern of orientation with respect to the applied stress.

5. The secondary crack density in the plate flexure fatigue tests averaged approximately one crack per centimeter of edge examined. This average was reasonably consistent at the three stress levels examined and was much lower than the crack density found on the rotating beam fatigue samples where secondary cracking occurred.

6. Much secondary cracking occurred on all of the plate flexure corrosion-fatigue specimens. This crack density was at a minimum at the intermediate test stress and increased as the test stress was either raised or lowered. These results indicate that, with a given corrosion solution and speed of testing, the combination of stress and length of test control the secondary crack density. The short time tests result in fewer defects recorded as pits or intergranular damage but the high stress of the test can open up more of these defects into visible cracks. The long time tests

provide more possible crack sites through pitting and corrosion which the lower stress can then open into cracks.

7. The lower speed plate flexure tests at the highest stress level seemed to promote the formation of transgranular corrosion-fatigue cracking over the "dry" transgranular cracking when compared to the results of the high speed tests. Except for this instance, explained by the difference in the length of time the specimens were exposed to the corrosive atmosphere, there was no major difference in the results obtained at two different testing speeds.

8. The crack types noted in the plate flexure corrosion-fatigue tests exhibited a consistent pattern. At the high stress the cracks are predominantly transgranular. As the stress is lowered and the time of test is lengthened, the damage becomes predominantly intergranular in nature. This same pattern is followed in the orientation of the damage in that it is mainly perpendicular to the surface at high stress and parallel to the surface at the low stress.

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