Proceedings of IMECE2005
2005 ASME International Mechanical Engineering Congress and Exposition
November 5-11, 2005, Orlando, Florida USA

IMECE2005-82906

CORROSION PREVENTION COMPOUNDS ON THE FATIGUE LIFE OF 2024-T3 ALUMINUM ALLOY

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KEYWORDS: corrosion prevention compounds (CPC), corrosion fatigue, fatigue life, periodic overload, and residual stress field

ABSTRACT
Corrosion-Prevention-Compounds (CPC) are commonly used to prevent corrosion in the aircraft industry. The presence of corrosive environment on aircraft structures has detrimental effects on the aircraft components which reduces the fatigue life and may also accelerate the crack growth rate in the structures. This is an experimental study on 2024-T3 aluminum alloy to investigate the effect of fatigue crack growth (life from threshold crack growth to final failure) using CPC on fatigue life. The corrosion fatigue with the presence of water-vapor reduces the total fatigue life. The fatigue life with the CPC treatment is shown to increase the fatigue life due to the protection from the corrosive environment containing water-vapor. Test results are obtained for various stress ratios and frequencies with and without the CPC treatment under constant amplitude fatigue loading in water vapor. The second aspect of this work is to investigate the effect of periodic overloads and the limitation in their spacing cycles on the fatigue life under constant amplitude fatigue loading. The results confirm the earlier work that the fatigue life increases due to the periodic overloads in 2024-T3 aluminum alloy. The interactions between overloads that are controlled by the spacing cycles between overloads are also examined. From scanning electron microscopic work the transition from the ductile to brittle mode is observed clearly in this experimental work.

1. INTRODUCTION
Several years ago, the major focus was on maintaining aircraft structures in their prime; today, the emphasis is on the care of the aged and extension of service lives beyond their design life. The bulk of the study is concentrated on two major fronts: the fight against fatigue and the control of corrosion. The coupled effects of corrosion, fatigue loading and their combined interactive effects on the durability of the structure is still not a completely known factor. Experimental studies indicate that while CPC are very effective in preventing corrosion within joint, in many instances they have also significantly reduced their fatigue life [1, 2]. This is due to the lubricative effect of oil and wax based corrosion prevention compounds that reduce the friction between fraying surfaces, consequently increasing the bearing load on the fasteners, which reduces the fatigue life of the joints. However, there is still considerable debate on this issue. In some cases no reduction in fatigue life has been observed. These disparities have been attributed to the variations in frequency or load ranges and also

many other factors. The presence of CPC at the crack tip can influence the rate of crack growth in the specimens directly by dispelling moisture from environment.

The second part of this work relates to the effect of periodic overloads during constant cycling amplitude loadings on the fatigue life. In general, the loading conditions are varied significantly in actual service conditions. Overload is a high peak stress out of constant amplitude spectrum. The residual stress field which is induced by an overload due to the load level exceeding yield strength of the material and subsequent unloading has beneficial effect on crack growth. The crack growth retardation due to a single overload ratio has been widely investigated in several studies [3-6]. The crack growth rate was found to be reduced after the application of overload and consequently, the fatigue life was increased due to overload. Crack growth analysis for variable amplitude loadings is not possible without an account of retardation effects. But, only a limited studies relating to periodic overloads are available [7, 8]. The mechanisms of Corrosion fatigue and overloads are discussed in the following section.

1.1 Mechanism of Corrosion Fatigue

The combined effect of the treatment with CPC on the corrosion fatigue life would be a compromise between the beneficial effect i.e. exclusion of moisture and the detrimental effect of the reduced friction between fraying surfaces (due to the lubricative effect of the corrosion prevention itself). These studies about the synergistic actions of corrosion and fatigue, however, have produced diverse and wide ranging results [9]. The reason is partly due to the large number of variables involved with this type of material behavior; but, in general the exposure to corrosive environment either prior to fatigue or during the cyclic loading significantly reduces the life of the component. The primary characteristics of corrosion fatigue life are that the crack growth rates can be substantially higher in the corrosive environment, because it either reduces the fatigue crack initiation life or it accelerates the crack growth rate or both. In this study, the emphasis is placed on the effects of environment (dry air, water vapor with and without CPC) and loading conditions (frequency and stress ratio) on the fatigue life [10]. In this work, the effect of CPC (LPS-3, a heavy duty corrosion inhibitor) on fatigue life under corrosive environment is being studied experimentally.

1.2 Mechanism of Overloads

Most structures experience some form of cyclic amplitude loading. High peak stress (overload) can also occur during this cyclic loading. This load fluctuation can lead to fatigue crack propagation, the rate of which depends on the interaction of load amplitudes. High peak overload can cause large immediate incremental growth, but sometimes can disturb the crack tip parameters and redistributes the stress field at the crack tip leading to retarded crack growth [11,12] during the cycles that follows peak overload depending on the overload ratio (OLR = $S_{overload}$ / $S_{constant\ amplitude}$) and the number of spacing cycles between the overloads. At the crack tip, the elastic stress would become very large due to the stress concentration factor. However, in practice large stresses do not occur because in a ductile material this region becomes plastically deformed. This causes a plastic zone at the crack tip. After unloading, the remainder of material will be elastic. i.e., the bulk of the material returns to zero strain after unloading. But, the plastic zone cannot return to the original size due to the plastic deformation. This plastic zone will be squeezed back to its original size. This causes the compressive residual stress field to occur at the crack tip. Therefore, after high peak overload, at the crack tip the compressive residual stress field will be present. During subsequent cycling this compressive residual stress will have to be added to the applied stress. The crack growth accounts for this compressive residual stress. The crack growth rate will be slower or retarded during the following cyclic loading due to the compressive residual stress along the crack plane. In other words, the fatigue life will be increased due to an overload. Single or periodic overloads induce such behavior. After each periodic overload, the crack growth rate is reduced due to the compressive residual stress field that is induced by overloads. Typically, crack closure does play a predominant role, but several other mechanisms also contribute to retardation such as residual compressive stresses ahead of the crack tip, shear lip effects, strain hardening, etc. In this work an experimental program was undertaken to study the effect of periodic overloads on fatigue life of 2024-T3 Aluminum alloy.

2. EXPERIMENTAL TECHNIQUE

2.1 Design of Test Specimen

In-plane yielding must be limited to the crack tip by guaranteeing that the net section stress is below yield strength. Specimen thickness, as it influences the degree of plane-strain constraint, and crack size, and also influences the chemical driving force. Accordingly, specimen thickness and crack geometry are treated as variables. Specimen thickness may affect crack growth rate, because transport of the environmental gases to the crack-tip may be the rate-limiting factor. In this work, center pre-crack Al 2024-T3 is used as a test specimen to study the fatigue crack growth rates (from threshold level to the failure of the specimens, ref; ASTM-E647-00), because it is relatively easy to maintain the specimen gage section at uniform temperature. In addition, in applying load to specimens in a corrosion chamber, care was taken so that chamber friction must not affect load in sealed systems. The geometry and dimension of test specimen are shown in Figure 2.1.

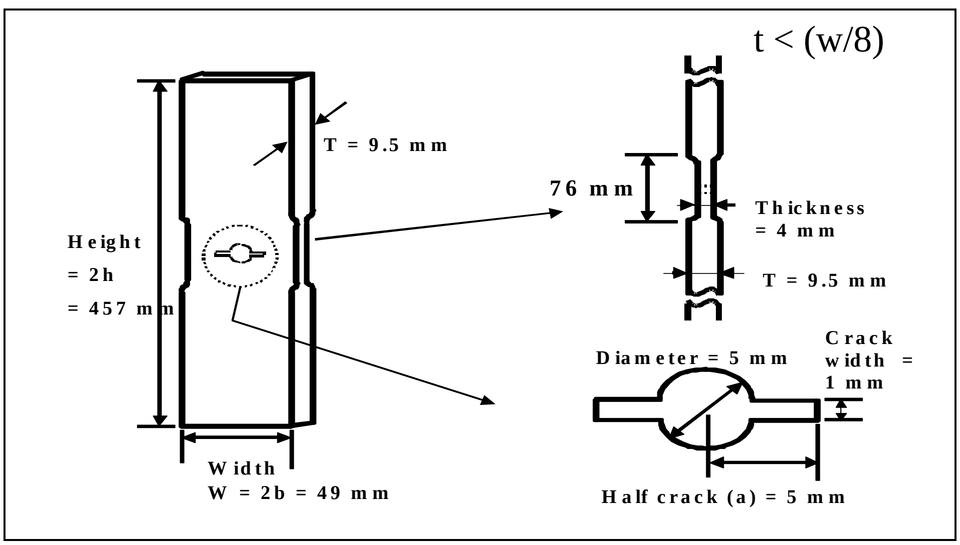

Figure 2.1 Geometry and dimension of test specimen-ASTM E647 [13]

2.2 Design of Corrosion Chamber

The corrosion chamber is made with a transparent plastic that enables the machine operator to visually monitor the progress of the experiment. A complete sealing between specimen and corrosion chamber is needed and accordingly, high effective seals between plastic and metal surfaces are made with silicon rubber caulking compounds and latex rubber. The decision to circulate the environmental liquid or gases depends on the application and the extent of any problem in controlling the environmental gases or liquid. The prevailing water chemistry in the environment is an essential factor in any simulated environment. Accelerated fatigue cracking can occur in a number of environmental conditions, including seawater, salt water/salt spray, and water-vapor. In this study, corrosive environment (water-vapor) is introduced with an ultrasonic humidifier. The humidifier produced soothing cool mist into the corrosion chamber through clean tubing.

2.3 Corrosion Fatigue under Water Vapor with CPC and without CPC

Specimens are tested per simulated conditions. In order to study the influence of frequency and stress ratio on the effect of fatigue life with and without the CPC, tests are performed with two separate frequency ratios, 0.5 Hz and 1.0 Hz and with two stress ratios ($R = S_{min} / S_{max}$) of R=0.2 and R=0.5. The MTS-810 Universal Testing System coupled with a PC is used to perform the required test. The water-vapor circulated within the transparent plastic corrosion chamber.

2.4 Experimental Methodology for Periodic Overloads Test

The objective of this part of the study is to determine the influence of the damage accumulation due to the periodic overloads on fatigue life on Al 2024-T3. This study was aimed at providing a more reliable basis for fatigue life predictions for various loading conditions. The metal structures that are subjected to differing loading conditions, the loading history dependence has a profound influence on fatigue life. In this study, a PC is coupled to the system to provide periodic overloads (Test-Ware-SX Version 4D). Under constant amplitude loading, periodic overloads are superimposed until a failure of the specimen attained during the test. An overload ratio of 1.7 (S_{ol} = 225 MPa, S_{max} = 150 MPa) is used. The spacing cycles between overloads are varied roughly between 20 and 5000 cycle. The stress ratio is 0.2 (S_{min} = 30 MPa, S_{max} = 150 MPa) and the frequency is 0.5 Hz. The objective is to find out the optimum spacing cycles between overloads for an overload ratio of 1.7 in order to get a maximum fatigue life until failure. Then, the number of cycles for each test required to grow the crack from the initial size to failure is recorded. Experimental facility showing various instrumentations is shown in Figure 2.2.

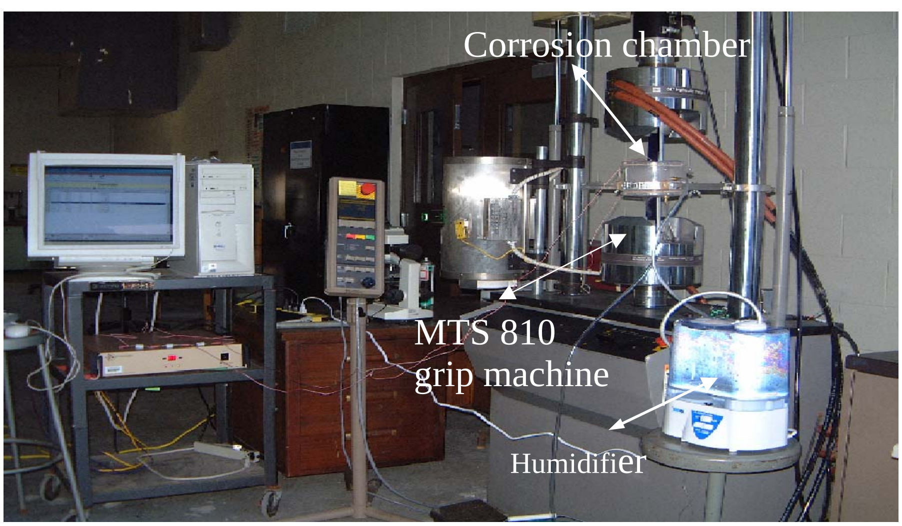

Figure 2.2 Experimental facilities (MTS-810, Strain smart software, and Corrosion chamber)

3. RESULTS & DISCUSSIONS

3.1 Corrosion Fatigue Testing

Many early experiments are performed in aiming at preventing corrosive effects within joints or fraying surfaces. In this study, new matrix is used with center pre-cracked specimen for fatigue crack growth rates under various environmental conditions with CPC and without CPC. Generally, the results (in Table 3.1) confirm that the increasing stress ratio has a detrimental effect on fatigue life for any environmental conditions. The increasing frequency didn't show the clear trend of either increasing or decreasing the fatigue life but may be some more conclusive tests could have been performed. Also, water vapor was found to have detrimental effects on fatigue life. The water vapor reduces the fatigue life except at R=0.5 with freq. at 1.0 Hz. In other words, to notice the effects of CPC on water vapor clearly the frequency needs to be decreased to allow more time to take place for producing corrosive effect. The water vapor tends to reduce the surface friction between crack faces during the fatigue loading. The result of the tests with CPC & water vapor generally show the beneficial effect of CPC on fatigue life. CPC does not protect the effect of water vapor on crack faces completely during the crack growth phase of the test. The fatigue life (CPC + Water Vapor at Freq. = 0.5Hz & R = 0.2), 15,231 cycles is greater than the fatigue life, 12,648 cycles at water-vapor even when the initial crack length is the same. There might be some small errors due to the difference of the initial crack length, the surface finish or the misalignment when the specimen is fabricated or gripped in the testing machine. Generally, the tests with CPC & water vapor show the 20 ~ 24 % increase of fatigue life than the test with just water vapor except the case of R = 0.5, and frequency = 1.0 Hz. Also, in order to see the effects of CPC on water vapor clearly, the frequency needs to be decreased to allow more time to take place for producing corrosion effect, and accordingly, tests were performed at a frequency of 0.5 Hz. When the results are compared between dry air and CPC + dry air, there is not a clear trend of improvement due to the application of CPC in dry air.

3.2 Overload Cycle Testing

The interaction between overloads is controlled by spacing cycles (50, 100, 200, 400, and 800 and so on) between overloads. The retardation associated with periodic overloads controlled by the periodicity spacing cycles between overloads is examined for overload ratio (OLR = S_{ol} / S_{max} = 1.7). The test result is shown in Table 3.2. From the results, the total fatigue life is enhanced dramatically when periodic overloads are superposed under the constant amplitude cyclic loading when these results are compared with the results described earlier. When the overloads are too close, for the densely applied spaced overloads, in case of spacing cycles n = 50, and 100, the total fatigue life is shorter than that of the remotely applied spaced overloads (spacing cycles, n = 800, 2000, 4000). The reason is that the interaction between overloads changes as the crack grows. In this work, there exists large range of cycle in-between the two overload cycles where the optimum enhanced retardation has occurred. To determine the largest total fatigue life for different spacing cycles needs more specific test results. It was reported [7, 8] that the maximum fatigue life at overload ratio = 1.65 occurred every 5000 spacing cycles. Generally, the total fatigue life increases as periodicity is increased until a peak is reached, followed by a decrease in total fatigue life afterwards. The overload interactions go through a maximum as the spacing cycle increases. Once the crack has grown through the overload plastic zone, the original crack growth rate will be resumed. At the peak total fatigue life, it starts decreasing. The optimum spacing cycles between overloads found in this test is in the range of 400 to 2000 cycles.

Table 3.1: Test result for various fatigue tests (unit: cycles)

Test Program	Freq. 0.5 Hz				Freq. 1.0 Hz			
	R = 0.2 (min:30MPa, max:150MPa)	R = 0.5 (min:75MPa, max:150MPa)	R = 0.5 (min:120 MPa, max:240MPa)	R = 0.2 (min:48MPa, max:240MPa)	R = 0.2 (min:30MPa, max:150MPa)	R = 0.5 (min:75MPa, max:150MPa)	R = 0.5 (min:120MPa, max:240MPa)	R = 0.2 (min:48 MPa, max:240 MPa)
Dry air	13466 cycles	11985 cycles	8550 cycles	9833 cycles	14021 cycles	12562 cycles	8850 cycles	9252 cycles
CPC + Dry air	13955	12978	7085	8148	14482	13468	6927	8435
Water vapor	12648	10878	7108	8032	12681	11673	7259	8500
CPC + Water Vapor	15231	14925	8576	9091	15831	15515	8993	9783

Table 3.2: Test result for periodic overloads tests (unit: cycles)

Spacing cycles between overloads	50	100	200	400	800	2000	4000
Overload Ratio 1.7	86,700	102,513	219,894	336,840	400,500	340,170	296,074

3.3 Results from Scanning Electron Microscope (SEM)

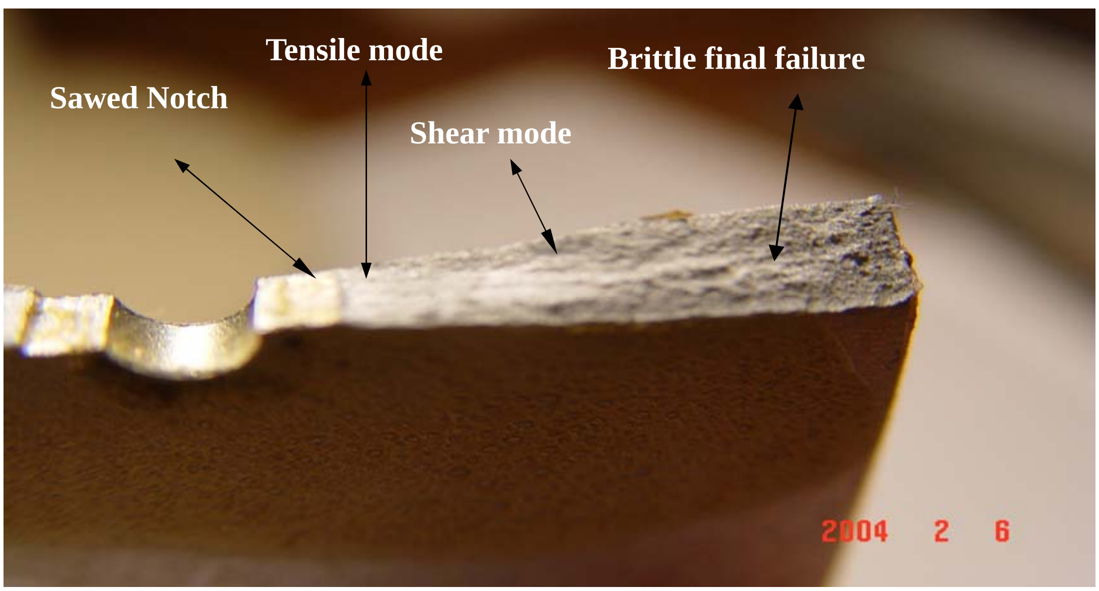

Figure 3.1 Fatigue crack surface showing transition from a flat tensile mode to an angular shear mode (at stress ratio=0.5, frequency=1 with CPC, LPS-3)

The fracture surfaces of the test specimens of Al-2024-T3 have been examined by a Scanning Electron Microscope (SEM) to characterize the failure processes. The SEM observations show two significantly different types of behavior for ductile fracture and brittle fracture. The fracture surfaces of the test specimen are investigated in order to see the effects of fatigue damage on the crack surface. To investigate the failure process, crack growth surfaces at several locations from the crack starter to the specimen failure are observed continuously in sequence. Several pictures were taken in sequence using SEM along the crack surface. The boundaries between grains are the weakest regions in the material, so that the crack grows along grain boundaries, i.e. inter-granular fracture. Inter-granular fatigue cracking occurred in case of brittle fracture. Figure 3.1 shows fatigue crack surface showing a transition from a flat tensile mode to an angular shear mode (at stress ratio=0.5, frequency=1.0 Hz with LPS-3) and each part is indicated in detail. A typical mode of ductile fracture is by void growth and ductile fracture is normally trans-granular. Void coalescence is the final stage in void-controlled ductile fracture. In this case plasticity is localized between voids. This localized deformation leads to final coalescence of voids and complete failure. The aluminum alloy exhibits a ductile rupture type of failure with micro-voids nucleating on the particles or precipitates (nucleation, growth and coalescence of voids [14]). These three sequential steps for fracture by voids are the major features of ductile fracture. This mechanism is called micro-void coalescence, which is also indicative of a ductile failure in case of Al-2024-T3. Figure 3.2 shows micro-void coalescence that is indicative of a ductile fracture and this figure is taken at the tensile mode. Tear dimples and micro-voids are found on the crack surface. Figure 3.3a&b show the dimpled rupture that is indicative of cleavage feature of a brittle fracture. These features developed during the fast fracture. The crack surface shows that the tear dimple pattern is initiated in Al-2024-T3. The tear dimples result from the application of non-uniform applied stresses and this tear dimples pattern is observed in the region of crack growth surface in this work.

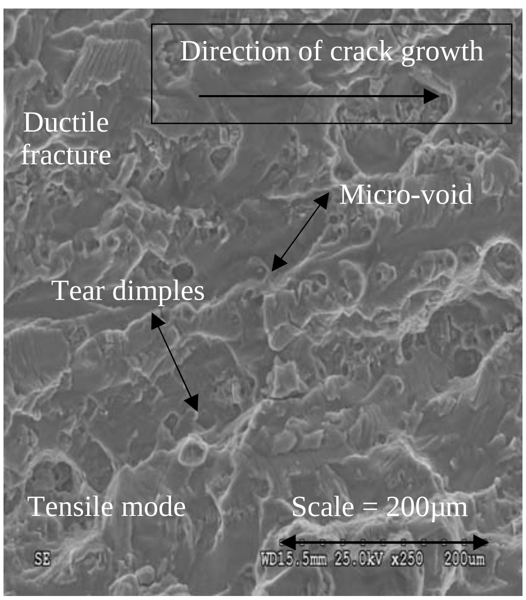

Figure 3.2 SEM micrograph for tensile mode tested at stress ratio=0.2, frequency=0.5 with dry air, (efer to figure 3.1)

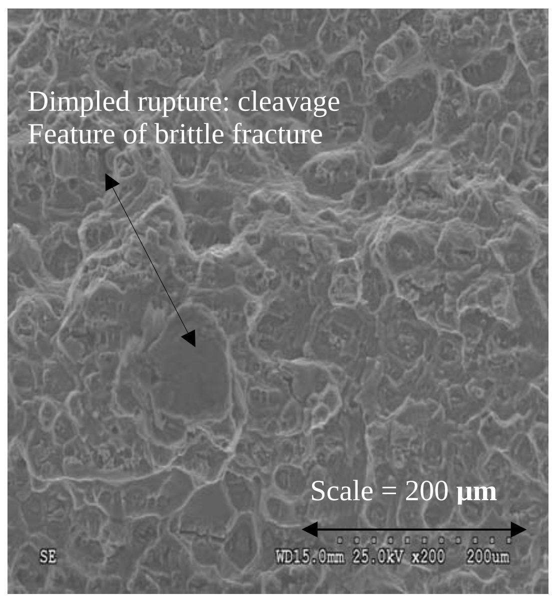

Figure 3.3a SEM micrograph for fracture mode tested at stress ratio=0.2, frequency=0.5 with dry air, (refer to figure 3.1)

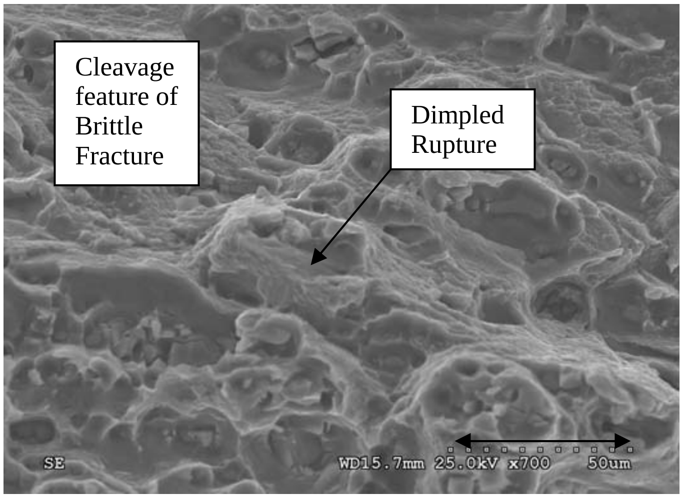

Figure 3.3b: SEM Micrograph for fracture mode tested at stress ratio =0.2, frequency = 0.5 with dry air (Refer to Fig 3.1).

CONCLUSIONS

The following general conclusions can be drawn from this experimental study. The corrosion fatigue in the presence of water-vapor reduces the total fatigue life. The fatigue life with the CPC treatment is shown to increase the fatigue life due to the protection from the corrosive environment of water-vapor. From the test results of various stress ratios and frequencies; with and without the CPC treatment subjected to constant amplitude fatigue loading in water vapor, generally, the tests with CPC & water vapor showed a 20 ~ 24 % increase of fatigue life in comparison to the test with water vapor only. In order to allow more time to take place for producing corrosion effect tests were performed at a frequency of 0.5 Hz and the results are compared between dry air and CPC + dry air, and there was not a clear evidence of improvement due to the application of CPC in dry air.

From the second investigation of the effect of periodic overloads on the fatigue life under constant amplitude fatigue loading, the results show that the fatigue life increases due to the periodic overloads in 2024-T3 aluminum alloy. The interactions between overloads that are controlled by the spacing cycles between overloads show that the maximum benefit is observed between overloads in the range from 400 to 2000 cycles for an overload ratio of 1.7.

From the SEM Micrographs of the failed specimen it has been found that there exist two distinct failure modes, i.e. ductile fracture and brittle fracture. The transition from the ductile mode to brittle mode is observed in this work.

ACKNOWLEDGMENTS

This work was sponsored by support received from the NASA Space Grant program under Grant NGT5-40115 and the Louisiana Board of Regents under contract NASA/LEQSF (2001-05)-LaSPACE (Grant Account #127-40-4103). Financial supports received from the LaSPACE Grant are acknowledged with thanks.

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