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# THE INFLUENCE OF CORROSION ON THE FATIGUE AND FRACTURE BEHAVIOUR OF 7050-T76 ALUMINIUM ALLOY SPECIMENS CONTAINING COLD EXPANDED HOLES.

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## Abstract

A test programme to assess the influence of corrosion on the fatigue performance of cold expanded fastener holes has been carried out at Kingston University on specimens of 7050-T76 aluminium alloy. Previous work on specimens subjected to prior atmospheric corrosion showed a 75% reduction in fatigue life when compared to non-corroded material due to cracks initiating from corrosion pits and causing premature failure. Tests at stress levels close to the fatigue limit of cold expanded specimens (175MPa) produced failure due to cracks originating from corrosion pits remote from the hole. At stress levels above 200MPa failures originated from the edge of the hole.

The current investigation examines the influence of the degree of corrosion on this transition. Tests at an applied stress close to the fatigue limit on specimens subjected to corrosion in 0.35% NaCl solution show that after a minimum period of 7 days in a salt bath, failure took place from cracks originating at corrosion pits. A microscopic investigation has been carried out to define the characteristics of these corrosion pits.

Tests were also carried out on specimens subjected to more severe corrosion (3.5% NaCl solution) with cold expansion performed prior to or after exposure to the corrosive environment. Cold expansion prior to corrosion exposure gave on average 66% better fatigue performance compared with specimens cold expanded after corrosion. These tests simulate the difference between the use of cold expansion for manufacture and for repair procedures.

## Notations

AT-CX: specimens corroded by atmospheric corrosion then cold expanded,
LCOR-CX: specimens corroded by low corrosion severity then cold expanded,
COR-CX: specimens corroded by high corrosion severity then cold expanded,
CX-COR: specimens cold expanded then corroded by high corrosion severity,
CX: specimens cold expanded with no corrosion,
LCOR-PL: specimens reamed only (plain) with low corrosion severity,
COR-PL: specimens reamed only (plain) with high corrosion severity,
PL: specimens reamed only (plain) with no corrosion.

## Introduction

The cold expansion process is a technique which has been in use for nearly thirty years to improve the fatigue performance of metallic structures containing fastener holes. This process has been used mainly during repair procedures on aircraft structures but is also now increasingly being used in initial manufacture. The cold expansion method used for this investigation is the split sleeve process developed by Fatigue Technology Incorporated (FTI) of Seattle, USA [1]. The process introduces residual compressive stresses around the circumference of the fastener hole which can improve the fatigue life of the structure by a factor (typically) of between 2 and 10. The compressive residual stress field around a cold expanded hole is balanced by a tensile residual stress field in an annulus of material surrounding the plastically deformed material. Cracks may be more readily initiated in this tensile residual stress region if there are any defects present and induced to propagate more rapidly due to these tensile residual stresses which may offset the beneficial effects of the cold expansion.

Previous investigations carried out at Kingston University have shown that cold expanded hole test specimens made from materials with prior atmospheric corrosion damage do exhibit significantly lower fatigue lives compared to those made from uncorroded material. The fatigue life observed in corroded material was on average less than 25% of that of the uncorroded material [2]. Further tests have been carried out on specimens which have been subjected to controlled corrosion by immersion in saline solutions. Analysis of corrosion pit formation and its effect on the fatigue process has been carried out. This included examination of the influence of corrosion pits on the initiation of cracks and the effects on crack growth period prior to failure. The influence of corrosion damage on fatigue life has been evaluated for specimens corroded both before and after cold expansion. The aim of this strand of the work is to compare the effectiveness of cold expansion used for new build and that used as a repair technique on material previously exposed to corrosion.

## Experimental Programme

### Fatigue test programme

A fatigue test programme was conducted using rectangular specimens 300 mm long, 40 mm wide, and 4.95 mm thick





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with a central hole. Specimens were manufactured in the LT orientation from 7050-T76 Aluminium Alloy. The chemical composition and the mechanical properties can be found in Ref. [3]. Three series of fatigue tests were performed, as described below, at a single constant amplitude stress of 175 MPa with a stress ratio of R= 0.1 and a frequency of 10Hz.
In the first series of tests, specimens had already been subjected to atmospheric corrosion. The material had been stored, unprotected for a period of about two years in a warehouse, and severe pitting corrosion had occurred. Two hole preparation methods were used, the first was a plain hole drilled and reamed to a diameter of 6mm. The second was a cold expanded hole with the same start diameter as the plain hole reamed after cold expansion to a diameter of 6.3 mm. The degree of cold expansion used was 4.25%. The main purpose of this series of tests was to investigate the effect of corrosion on the effectiveness of hole cold expansion.

The second series of tests were undertaken to examine the effectiveness of hole cold expansion in components subjected to controlled corrosion conditions. The objectives were to examine the degree of corrosion required in order to produce premature fatigue failures from corrosion pits. Two cases were considered, cold expansion prior to corrosion (representing cold expansion at aircraft build) and cold expansion after exposure to the corrosive environment (representing cold expansion as a repair procedure). Two batches of aluminium alloy were subjected to severe corrosion (immersed in salt solution of 3.5% NaCl) for the same length of time. The first batch were cold expanded prior to exposure to corrosion (CX-COR specimens) whilst the second batch were cold expanded after corrosion (COR-CX specimens).

It was found that specimens subjected to the above corrosive environment prior to cold expansion all failed from corrosion pits even after exposure times as short as five minutes. A third series of tests was conducted, therefore, at a lower corrosion severity (immersion in a solution of 0.35% NaCl) to assess the influence of the degree of corrosion. Testing focused on specimens cold expanded after exposure to the corrosive environment (LCOR-CX specimens). In the high and low corrosion severity tests, plain reamed only specimens were also tested. Specimens subjected to artificial corrosion were rinsed with distilled water, cleaned with acetone and stored in a dessicator before and after exposure to the corrosive environment.

A surface replication technique using cellulose acetate sheet softened with acetone was used to monitor crack initiation and growth both in the bore of the hole and on the plate surfaces. Cellulose acetate replicas on the plate surfaces covered an area of up to 15mm above and below the centre-line of the hole over the whole width of the specimen. Replication was performed with a static load applied to the specimen of 80% of the maximum cyclic load to ensure crack surface separation. Replicas were examined and the crack lengths were measured using a "Shadowgraph" projector.

Microstructure and fracture surface investigations

When fatigue tests were complete, specimens were examined in a scanning electron microscope to determine crack nucleation sites and corrosion pit characteristics. X-ray analyses were also performed in order to examine the corrosion products present.

Four different investigations were also carried out using optical microscopy. In the first, microstructure was examined in the LT, ST and TL planes for cold expanded and non cold expanded non corroded specimens. Particular attention was taken to compare the microstructure in the compressive and tensile residual stress regions. The second investigation focused on observations of specimen surfaces which had been immersed in low or high corrosion severity for different length of time to determine whether different sizes of corrosion pit had formed after different exposure times. The third investigation involved sectioning of cold expanded specimens which had been exposed to corrosive environments and examining corrosion pit shapes through the material thickness (ST direction) to determine any differences in corrosion pit shapes for specimens cold expanded prior to corrosion (CX-COR) and after corrosion (COR-CX and LCOR-CX). In the first three investigations, specimens were polished to 1 μm and etched using Keller's reagent for 60 seconds. The final investigation was performed on the acetate replicas to determine whether surface cracking at the pits resulted from the cold expansion process. The replicas were uncoated but polarized filters were used. By varying the polarisation direction of one of the filters, the fraction of light reflected from the surface of the replica was increased, producing a better image. Corrosion pits as small as 4.5 μm in diameter could be observed by this method.

## Analytical programme

Crack growth rate prediction

A Linear Elastic Fracture Mechanics (LEFM) model considering Mode I cracks was used which took into account the residual stresses formed during the cold expansion process. The residual stresses were determined by X-ray diffraction method using the $\sin^2 \Psi$ method [4]. The small penetration depth of X-rays resulted in the determination of near surface strains only. Fig 1 shows the measured residual hoop and radial stresses for the mandrel inlet and outlet surfaces after the cold expansion process. The mandrel inlet face in a cold expanded specimen is defined as the face opposite where the mandrel was inserted, the outlet being the face where the mandrel exits the specimen. The area irradiated by the X-ray beam is about 0.5mm square, consequently the region of compressive yielding close to the hole edge is not well defined by this method. The areas of compressive yielding have been estimated from boundary element analysis and distributions chosen such that when averaged over successive 0.5mm volumes gave the same residual stresses as those measured by the X-ray method. The stress distributions were measured along the minimum section of the specimen where cracks would be expected to grow.

Finite Element Analysis modelling a quarter of the specimen in tension has been used previously to determine the stress distribution resulting from external loading [3]. The area where cracks were found growing from pits was divided into 0.5mm intervals in the x and y directions and the axial stresses determined from the sum of the residual and applied stresses at each resulting node. It was observed that the stress range $\Delta\sigma = (\sigma_{appmax} - \sigma_{appmin})$ was approximately uniform in the x direction for a distance of several millimetres at each node.
The stress ratio $R= [(\sigma_{appmin}+ \sigma_{res})/ (\sigma_{appmax}+ \sigma_{res})]$ was also calculated at each node.

The stress intensity factor distribution for each potential crack site (node) was calculated assuming that the alternating stress distribution was uniform and that the pit could be represented by the semi-hemispherical solution proposed by Murakami [5]. Thus for each node the stress intensity factor distribution was calculated. The next step was to calculate crack growth rates corresponding to the calculated stress intensity factor as a function of crack length. This was accomplished using a set of 7050-T76 material crack propagation data at a series of stress ratios. Growth rates were determined by interpolation between the data sets for the stress intensity factor and stress ratios calculated by the above method. A graph showing some experimental and predicted crack growth rates as a function of crack length is shown in figures 2 and 3. Figure 2 presents the predicted and measured growth rates from a pit located in the compressive residual stress region and figure 3 presents data from seven different tests where the cracks causing failure grew from pits located in similar areas of the tensile residual stress region. The results presented in figure 4 represent crack growth rate measurements from all of the tests conducted on cold expanded specimens exposed to corrosive environments regardless of the location of the corrosion pit from which the critical crack grew.

## Results

## Experimental programme

### Crack initiation positions

The results of the first series of tests with specimens corroded by atmospheric corrosion showed that all the specimens failed from cracks initiating at corrosion pits. In 82% of the cases, the crack causing failure initiated on the mandrel outlet face and for the majority (80%) the initiation sites were in the tensile residual stress region. In addition to the main crack, additional cracks typically less than 2mm in length were found at many other corrosion pits. The initiation sites of these secondary cracks were also mainly situated in the tensile region (96%). However, only 60% of these secondary initiation sites were located on the mandrel outlet face. Considering all cracks formed at pits, the percentages formed on the mandrel inlet and outlet faces are similar (46% and 56% respectively).

Under controlled corrosion, specimens severely corroded prior to cold expansion had secondary cracks in similar locations to those described above located with equal probability on the mandrel inlet and outlet faces. However, cracks causing failure initiated principally in the tensile region (92%), of which 54% located on the mandrel outlet face. The distribution of all cracks found at pits was 52% on the mandrel outlet face and 48% on the mandrel inlet face.

A different failure mode appeared when the specimens were cold expanded before exposure to the severe corrosive environment. Most of the specimens (82%) failed due to a crack starting at the edge of the hole, of which 97% were on the mandrel inlet face. Out of 28 specimens, 5 failed at a position remote from the hole of which 4 were on the mandrel inlet face. Secondary cracking was also found at corrosion pits of which 67% were found on the mandrel outlet face. The distribution of all cracks found was 46% on the mandrel inlet face and 54% on the mandrel outlet face.

At low corrosion severity, a wider range of immersion times were used varying from 1 hour to 30 days. All specimens subjected to exposure times of less than 8 hours failed from cracks initiating at the hole. For exposure times between 8 and 48 hours 66% of the cracks which caused failure initiated at the hole. At exposure times greater than 48 hours, initiation sites which caused failure were evenly distributed between the hole and remote locations. Smaller secondary cracks at pits were found which were evenly distributed between the mandrel inlet and outlet faces in the tensile residual stress region.

### Fatigue Life Analysis:

Table 1 presents the average nucleation and growth periods of cracks causing failure and the total fatigue lives of specimens tested in the different test series. For the two test series without cold expansion, specimens which were reamed only (PL) gave similar fatigue performance to specimens which were reamed only and then subjected to high severity corrosion (COR-PL). This indicates that exposure to corrosive environments prior to testing alone has little observable effect on the location of crack nucleation or on the fatigue crack nucleation and growth periods.

This is not the case when cold expansion has been used after exposure to corrosive environments as in many cases cracks now initiate from corrosion pits remote from the hole. In order to determine the effects on fatigue behaviour of these various corrosive environments, comparisons can be made of test results in which specimens were exposed to atmospheric corrosion (AT-CX), controlled corrosion of low severity (LCOR-CX) and controlled corrosion of high severity (COR-CX) prior to expansion. All specimens exposed to atmospheric and high severity corrosion failed from initiation sites remote from the hole, as did some specimens exposed to low severity corrosion for extended periods. Comparing the fatigue behaviour of specimens in the three test series which failed remotely from the hole, it can be seen that the nucleation periods are longest for low corrosion severity (LCOR-CX 96,375) and shortest for atmospheric corrosion (AT-CX 41,156). This indicates that for cold expanded holes, prior corrosion does affect the nucleation period. This is to be expected as the amount of damage created by the different corrosive environments will affect the nucleation periods of cracks forming remote from the holes. The results suggest that the greatest corrosion damage was formed by atmospheric corrosion (nucleation of 41,156), similar or slightly less damage by the severe corrosion environment (nucleation of 52,597) and the least damage was created by the low corrosion severity (nucleation of 96,375). This is in line with what is expected based on the exposure times and the severity of corrosive environment. The crack growth periods were similar for the two artificial corrosion types (62,862 and 62,250) but slightly longer for the atmospheric corrosion tests (76,435). It is expected that the growth periods should be the same since these are controlled primarily by the stress fields which are similar in all test types. The slightly greater growth period in the atmospheric corrosion tests could result from shielding of the main crack by the large number of secondary cracks which formed. It can be concluded that corrosion prior to cold expansion has a significant influence on the location of fatigue failure. If failure occurs from pits remote from the hole, the fatigue nucleation period is affected by the severity of the different corrosive environments and exposure times but the crack growth period is little affected.

The fatigue endurances of specimens which failed from the hole at short exposure times to the low corrosion severity (LCOR-CX) are greater (177,772) than those from tests which failed from remote locations (117,591, 115,449 and 168,736 for atmospheric, high and low corrosion severities respectively). These are tests in which specimens were exposed to low severity corrosion for short periods (less than 8 hours) where corrosion pits of sufficient size had probably not developed making the hole the most critical region. In all tests with corrosion prior to cold expansion, cracks formed at the hole whether or not they were cracks which caused failure. It can be seen from Table 1 that nucleation periods for cracks at the hole were similar in all test types (52,103, 56,104, 56,986 and 59,921). This is very much as expected from an examination of the results of the plain hole tests where corrosion had no effect on the nucleation period of cracks at the hole. The crack growth periods in tests with short exposure times to low severity corrosion (LCOR-CX), where cracks which cause failure grow from the hole (117,851), are much greater than those for tests in which failures initiate from corrosion pits (62,250 to 76,435). This is because of the different stress fields through which the cracks grow. The stress field away from a cold expanded hole has high compressive residual stresses, which extend for several millimetres, but high alternating stresses due to the stress concentration. This results in a smaller effective stress field compared with that around a corrosion pit which has moderate tensile residual stresses and low alternating stresses. The effective stress at the two locations was derived in a previous publication [3]. It can be concluded that the total fatigue endurances of specimens which fail from pit origins are shorter than those of specimens which fail from cracks initiating at the hole. Wherever failure occurs, cracks nucleate at the hole and the nucleation period is not affected by corrosion.

Tests were also performed in which cold expansion was carried out prior to high corrosion severity exposure (CX-COR). As observed above, 82% of failures occurred from cracks which grew from the hole. From the foregoing discussion, it is expected that the nucleation and growth periods of cracks which grow from the hole will not be affected by corrosion severity or exposure times. An examination of Table 1 shows this to be the case, the nucleation periods and growth periods being similar to those of LCOR-CX tests which also failed from cracks originating at the hole. Similarly, from the foregoing discussions, it is expected that the nucleation period of CX-COR specimens which failed from pit origins will be dependent on the degree of corrosion severity and should therefore be similar to those observed in the COR-CX tests. This was not the case, as can be seen from Table 1 where the nucleation periods were 90,735 and 52,597 for the CX-COR and COR-CX tests respectively. The nucleation period for the CX-COR tests was in fact more similar to the LCOR-CX tests suggesting that the effect of corrosion severity is not the same when applied before and after cold expansion. Also from the foregoing discussions it is expected that the growth periods for CX-COR tests in which remote failure occurred should be similar to those for the other test series in which remote failures occurred. This is again the case, as can be seen from Table 1, where the growth period for the CX-COR tests was 64,856 compared with 62,862 to 76,435 for the other test series.

The main questions deriving from the CX-COR tests are why do the majority (82%) of failures occur from the hole when in COR-CX tests all failures occur remote from the hole, and why is the effect of corrosion severity not the same for tests in which cold expansion was performed prior to corrosion compared with those in which cold expansion was performed subsequent to corrosion. These issues will be addressed later in the discussion.

Microstructure and Fracture Surface Observations

Scanning Electron Microscopy

A wide variety of corrosion pit sizes and shapes were found from specimen examination in the scanning electron microscope. However, the variations observed occurred for all test series and could be found in each test specimen. No consistent trends in pit shapes, sizes or distributions were observed in the four test series. A typical example of a corrosion pit is presented in figure 5. In this particular case, the specimen was corroded at low corrosion severity for 7 days. The 'feathery' markings converged to the initiation point on the mandrel outlet face where two corrosion pits were found next to each other. The pits were located 8.6 mm from the edge of the hole and 1.2 mm from the specimen centre-line where the applied, hoop and radial stresses were respectively 180, 0 and 0 MPa. The corrosion pit on the right hand side was 150 μm in diameter and 70 μm deep while the dimension of the left hand corrosion pit was 75 μm in diameter and 50 μm deep. The specimen surface appeared very rough and was disrupted by the presence of pit blisters. This area was also found on specimens corroded by atmospheric corrosion. X-ray analysis of these particles shows the presence of Aluminium, Zinc, Copper Magnesium, Chlorine, Oxygen and Carbon.

Optical Microscopy

Specimen surfaces were examined using optical microscopy and no differences in the microstructure were observed between cold expanded and plain hole specimens. Detailed examination of the microstructure was made at various locations on the surface of cold expanded specimens and no differences in the grain structure could be seen in the tensile or compressive residual stress regions.

The surfaces of specimens exposed to corrosive environments prior to cold expansion (LCOR-CX and COR-CX) and after cold expansion (CX-COR) were examined by optical microscopy and typical examples are presented in figures 6, 7 and 8 respectively. The pits presented in the figures are typical of those found in any specimen subjected to the controlled corrosive environments and are not meant to be representative of pits found in specimens exposed to each of the corrosive environments used. An interesting type of corrosion observed in a specimen after only 4 hours of immersion in the high corrosive environment is presented in figure 9. This shows extensive subsurface cracking below the corrosion pit.

Observations were also made of the acetate surface replicas after exposure to the corrosive environment and cold expansion had taken place, but prior to fatigue loading. There was no evidence on any of the replicas examined of cracking from the corrosion pits. Cracking was only observed after a period of fatigue cycling and cracks appeared to initiate mainly from the pit blisters.

Analytical Programme

Crack growth rates were predicted at each pit location observed during testing where cracking caused specimen failure. The locations were grouped based on the local stress and stress ratio prevailing at the pit. Two typical examples of predicted crack growth rates are presented in figures 2 and 3 for each of two such groups. Figure 2 shows the predicted and measured growth rates from a corrosion pit located in the compressive residual stress region where the local stress ratio was calculated to be R= -0.45. This was the most compressive stress ratio found for cracks causing failure. Only one failure occurred at this stress ratio. The data presented in figure 3 are for cracks originating from pits located in tensile residual stress region where the local stress ratio was calculated as R=0.25. The experimental measurements are from seven tests and this represents the highest stress ratio at which critical cracking was found. Similar predictions were produced for seven other groups of pit locations and the general conclusion was that reasonable correlation was found between experimental and predicted growth rates in the elastic region, but that agreement was poor in the plastic region. In the plastic zone, the experimental crack growth rates were always faster than predicted.

Measured crack growth rates are presented in figure 4 for all of the tests in which failure occurred remote from the hole. Also shown in this figure are crack growth data measured in a previous investigation for 7050-T76 material tested at a stress ratio of R=0.1 (the test stress ratio). It can be seen that there is very little scatter in the test data measured in the current test programme. This is slightly surprising since the location of the pits from which crack growth occurred covered a wide area where the stress ratios varied from -0.45 to 0.25. However, it can be seen that the predictions indicate that a single stress ratio slightly greater than R=0.1 would result in good correlation with the experimental data at stress intensity factors greater than about 3 $MPa.m^{1/2}$. At stress intensity factors below this value the experimental growth rates are much faster than predicted and do not appear to have an obvious threshold. There are many possible reasons for this as described below. The first is that cracks are very short in this low stress intensity region and short cracks have been shown to grow much faster than long cracks at the same calculated stress intensity factor, and also to grow at stress intensity factors smaller than the long crack threshold [6]. The second possible reason is that the stress intensity factor distribution does not adequately describe the region around a corrosion pit. This is quite likely since the solution used is for a hemispherical defect whereas corrosion pits are very complex in shape and will have much larger stress concentrations than a hemispherical defect. The third possible reason is that there are residual stresses associated with the corrosion pit resulting from the cold expansion process. The final reason is that subsurface cracks could initiate in the region where intergranular cracking was observed and could be growing quite rapidly when they break the specimen surface and are measured by the surface replication technique.

## Discussion

Cold expansion of fastener holes is used in the aircraft industry to enhance fatigue performance. The benefits accrue from the compressive residual stresses formed during the cold expansion process. These compressive stresses increase the nucleation period of cracks growing from the cold expanded hole, but more importantly retard the rate of growth of such cracks. The compressive residual stress region, in an annulus of material surrounding the hole, is constrained by a larger annulus of material surrounding the compressive residual stress region in which the residual stresses are tensile. The compressive residual stress region is deep acting (several millimetres from the hole) and contains residual stresses close to the compressive yield stress of the material. Consequently, in order to maintain equilibrium, the tensile residual stress region is expansive (tens of millimetres) but contains only moderate stresses (less than 100MPa). It is of concern that cracks could nucleate and grow in these tensile residual stress regions and negate the benefits of the cold expansion process. Any stress concentrating features in the tensile residual stress region may initiate such cracks. These stress concentrations could result from material or manufacturing defects or from service induced defects such as fretting of joined surfaces, impact damage or corrosion. Since corrosion is extremely common in aircraft structures, it was decided to examine the role of corrosion on the beneficial effects of hole cold expansion.

Cold expansion of open hole specimens manufactured from 7050-T76 material was found in previous investigations [7] to enhance the fatigue endurance and the degree of life enhancement was found to be dependent on the applied stress range. A stress ratio of R=0.1 with a peak nett section stress of 175MPa was selected for this investigation as it resulted in fatigue endurances close to the fatigue limit of cold expanded specimens which would be typical of stresses used in aircraft wing structures. The investigation described in this report examined two specific areas of relevance to aircraft structures, the use of cold expansion in repair and the use of cold expansion at build. The test series were defined to examine these two areas by investigating the effect of corrosion prior to cold expansion (cold expansion as a repair) and after cold expansion (cold expansion at build). The effect of cold expansion on non-corroded material had already been determined, as mentioned above, so this investigation considered only the effects of corrosion on the effectiveness of hole cold expansion.

The first series of tests to be undertaken involved material which had been subjected to atmospheric corrosion for a period of about two years (AT-CX). Specimens were cut from this material and subjected to the fatigue loading described above. The main conclusion from this series of tests was that fatigue endurances were significantly shorter than cold expanded specimens manufactured from non-corroded material. The reason for this reduction in fatigue endurance was attributed to crack nucleation from pits in the tensile residual stress region which caused premature failure of the specimens from cracking remote from the hole. A stress analysis of the components was carried out which showed that although the effective stresses were largest close to the hole, the effective stresses decreased rapidly with distance away from the hole. Effective stresses of slightly smaller magnitude than those at the hole were present in the tensile residual stress region which extends over a large area. It follows that if cracks nucleate remote from the hole, they are more likely to grow than cracks emanating from the hole. It was concluded that corrosion pits were the nucleation site for cracking and that the tensile residual stresses present created an effective stress distribution greater than that at the hole which resulted in premature failure of the specimens.

Following this investigation it was apparent that long exposure to atmospheric corrosion resulted in remote premature failure of cold expanded specimens but there was no indication of how severe the corrosion had to be before remote failures occurred, and there was no quantification of the sizes of pits which had formed. The second investigation (COR-CX) was started in order to answer these questions. Specimens were exposed to 3.5% NaCl solution for various periods to determine how much corrosion exposure was required before premature remote failures occurred. This corrosive environment was selected as it is widely used in the aerospace industry to accelerate corrosion in laboratory investigations. Unfortunately, even with short exposure times of about 5 minutes, premature remote failures occurred in all tests. Despite the remote failures, cracks also formed at the holes in the high effective stress regions but the cracks decreased in growth rate as they grew into the increasingly compressive residual stress field. Tests were also performed on plain non-expanded hole specimens and it was shown that corrosion did not affect the location of failure, as all tests failed from cracking at the hole, nor did it affect the fatigue endurances.

As the above test series did not produce failures from the hole with cold expanded specimens, the corrosion severity was reduced by using a 0.35% NaCl solution (LCOR-CX). This resulted in failures from the hole at low exposure times of less than 8 hours, the majority of failures from the hole (66%) at exposure times of between 8 and 48 hours, and an even mixture of remote and hole failures at longer exposure times. Beyond 7 days most failures were remote (80%). The deleterious effects of corrosion can be observed from these test results where specimens in which failure occurred from remote cracking had much shorter endurances than those in which failure occurred from the hole. An examination was made of crack nucleation periods at the hole in each of the above test series and it was found that nucleation periods were independent of exposure times to atmospheric, low severity or high severity corrosion. This is in line with the results from the plain hole tests described above. A similar examination was made of crack nucleation periods for cracks forming remote from the hole. In this case the nucleation period was dependent on the corrosive environment and was longest for low severity corrosion and greatest for high severity corrosion. Crack growth periods were also examined from remote failure tests and it was found that the growth periods were similar for all corrosion types. This was expected as the stress fields which determine fatigue crack growth rates were similar in all tests.

Having established the effect of corrosion severity on crack nucleation and growth periods at the two possible initiation sites for specimens cold expanded after exposure to corrosion, it was decided to determine whether similar behaviour would occur in tests where cold expansion was carried out prior to exposure. The next test series (CX-COR) was carried out with the exposure to the high corrosion severity following cold expansion. Markedly different behaviour from that observed in the COR-CX tests was observed in these tests, with 82% of specimens failing from cracks emanating from the hole. Since the corrosion severity, exposure times, and fatigue loading were identical to the COR-CX series of tests described above, it was concluded that the cold expansion process must affect the corrosion pits which had already formed in the COR-CX tests. This was evaluated by microscopic examination of the replicas used to monitor crack growth. It was found that no cracking was observed at the corrosion pits following the cold expansion process, but that cracking did occur after some fatigue loading had been applied. An SEM examination of the fracture surfaces also revealed no apparent differences between the appearance of the pits which caused failure in the two test series. A possible explanation was found from microscopic examination of sectioned specimens to examine the corrosion pit shapes in the thickness of the material (ST orientation). Here it was found that below the pits subsurface intergranular cracking was present in specimens which had not been subjected to fatigue loading. It is thought that cracking during fatigue loading actually initiates from this region. This is supported by the crack growth measurements which were made on the surface of specimens cold expanded after exposure to the corrosive environments. Measured crack growth rates were much faster than predicted at short crack lengths but were reasonably accurate at longer crack lengths. The measured growth rates did not exhibit any threshold behaviour and grew at stress intensity factors below the long crack threshold value. This is entirely consistent with subsurface initiation resulting in rapid surface growth once the crack breaks through to the specimen surface. There are a number of other possible explanations of this crack growth behaviour, the most obvious being the short crack effect which has been widely reported [(6)]. However, this is more commonly observed at negative stress ratios and under spectrum loading. Small crack effects have not been generally observed at stress ratios of R=0.25 which is typical of growth from pits in these tests. A further study is required to confirm these observations and to identify the 'damage' caused by cold expanding corroded material.

The observed behaviour has implications to the aircraft industry where cold expansion is utilised. It should be borne in mind that despite the deleterious effects of corrosion described in this paper, cold expansion still provides significant life enhancements. The results of this work do not suggest that cold expansion should not be used on potentially corroded structure, rather that the methods used to qualify the repair should account for the corrosion and that inspections should include areas remote from the hole in cold expanded structures.

## Conclusions

1. Cold expansion of corroded material can give significantly smaller fatigue life enhancement than cold expansion of non-corroded material.

2. Cold expansion of corroded material can result in failures remote from the cold expanded hole.

3. The degree of corrosion prior to cold expansion controls the failure location.

4. The degree of corrosion controls the crack nucleation period of cracks initiating remote from the hole.

5. Remote failures occur from corrosion pits, predominantly in the tensile residual stress region.

6. Corrosion has no noticeable effect on the fatigue endurance of plain hole specimens and failures always initiate at the hole.

7. Corrosion prior to cold expansion has no effect on fatigue endurance if failures initiate from the hole.

8. Exposure to corrosion after cold expansion has little effect on fatigue life enhancement as cracks initiate predominantly from the hole.

9. Exposure to corrosion after cold expansion can affect the fatigue life enhancement if failures initiate at remote locations.

10. Cold expansion creates some form of additional damage at corrosion pits; this is thought to be subsurface intergranular cracking.

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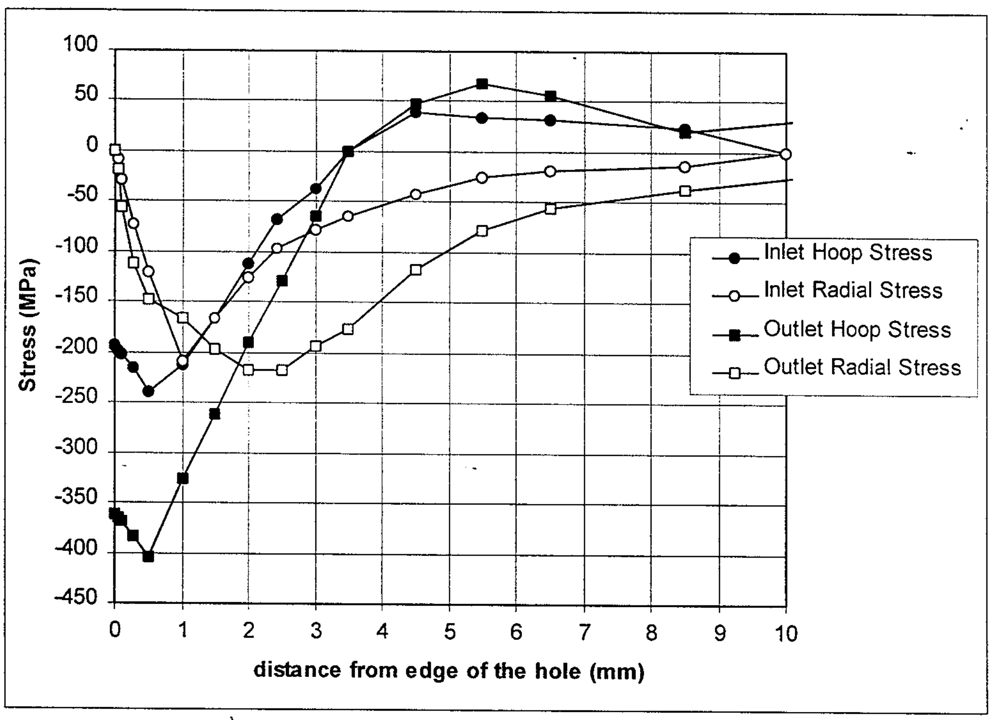


FIGURE 1- Residual stresses induced by the cold expansion process.

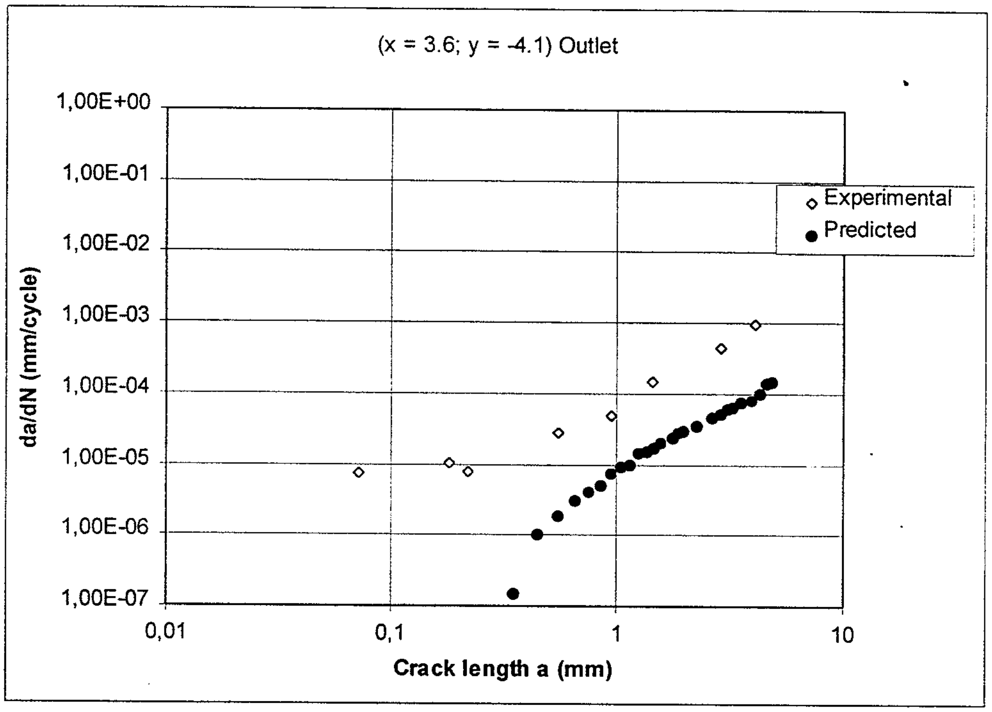


FIGURE 2- Crack growth rate from corrosion pits in cold expanded specimens (R= -0.45).

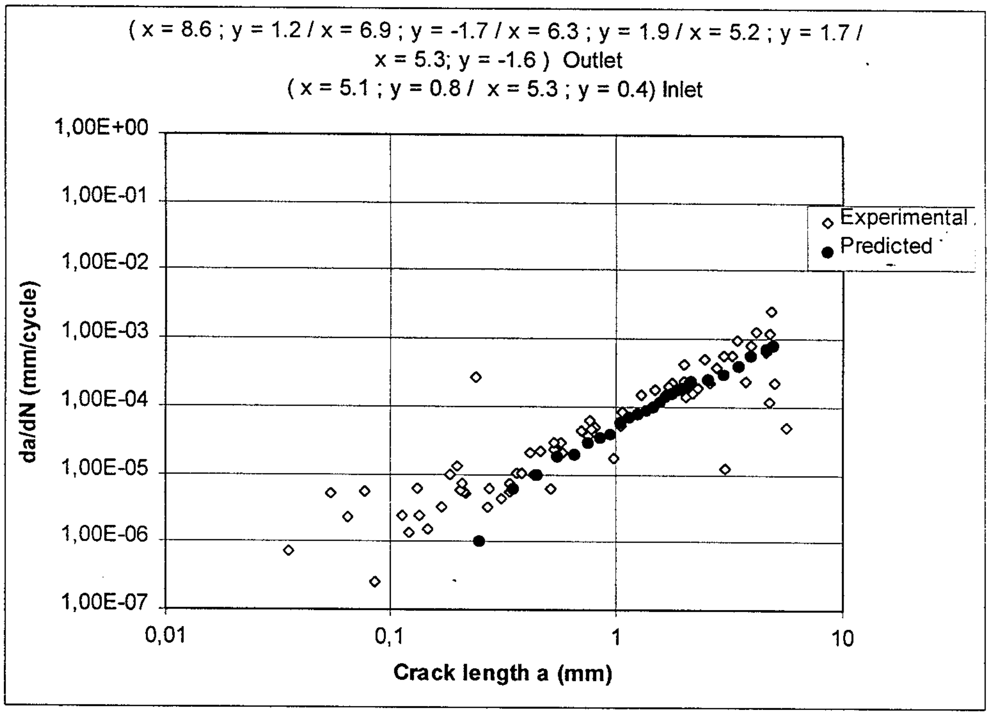


FIGURE 3- Crack growth rate from corrosion pits in cold expanded specimens (R= 0.25).

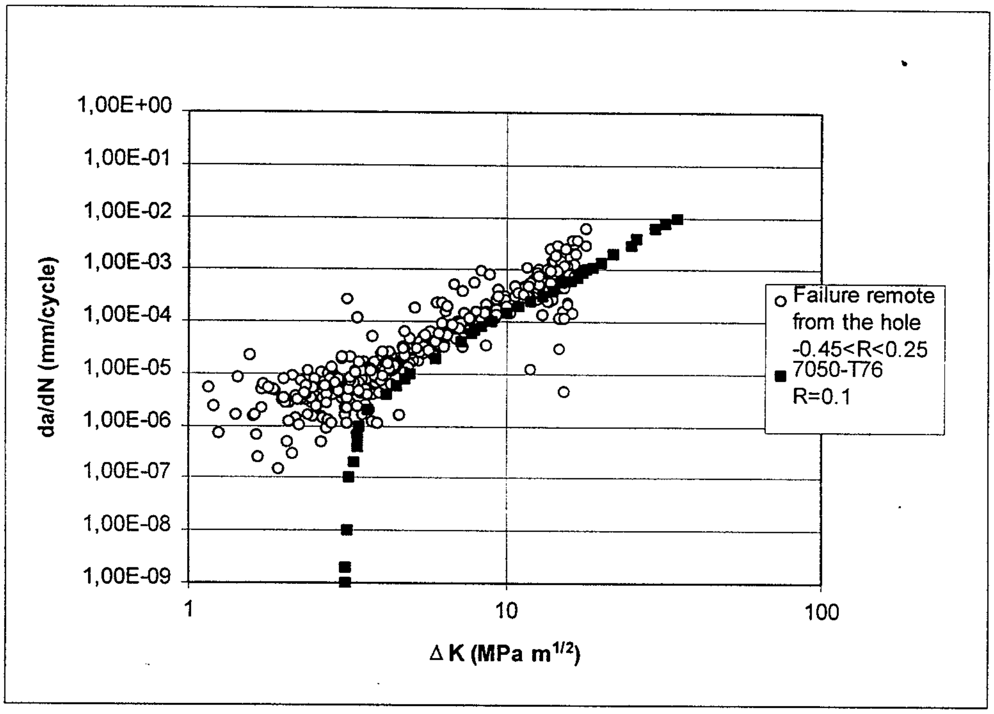


FIGURE 4 – Crack growth rate from corrosion pits in cold expanded specimens.

| Specimen | Nucleation Period (cycles) | Crack Growth Period (cycles) | Total Fatigue Life (cycles) |
|---|---|---|---|
| COR-PL | 15,874 | 5,411 | 21,285 |
| LCOR-PL | 13,490 | 6,313 | 19,803 |
| PL | 13,666 | 8,760 | 22,426 |
| AT-CX (all **Remote**) | 41,156 | 76,435 | 117,591 |
| COR-CX (all **Remote**) | 52,597 | 62,862 | 115,469 |
| LCOR-CX **(Remote)** | 96,375 | 62,250 | 168,736 |
| CX-COR **(Remote)** | 90,735 | 64,856 | 155,591 |
| LCOR-CX ***(Hole)*** | 59,921 | 117,851 | 177,772 |
| CX-COR ***(Hole)*** | 56,104 | 108,023 | 164,127 |
| LCOR-CX H*ole* but **failed Remote** | 56,986 | N/A | N/A |
| CX-COR *Hole* but **failed Remote** | 52,103 | N/A | N/A |

The nucleation period is the number of cycles for a crack to reach a length of 0.1 mm.
The crack growth period is the number of cycles for a crack to propagate from 0.1 mm to failure.

Table 1. Crack nucleation and growth data for all fatigue test specimens (log mean values).

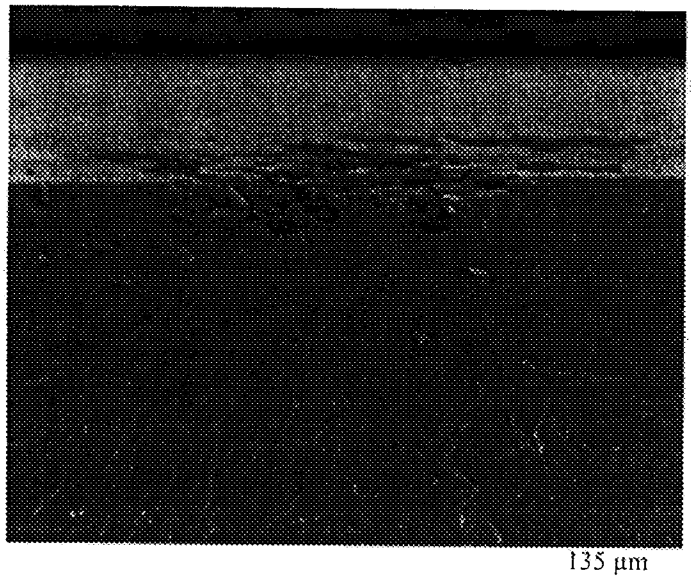


FIGURE 5 – Typical crack initiation site at corrosion pit.

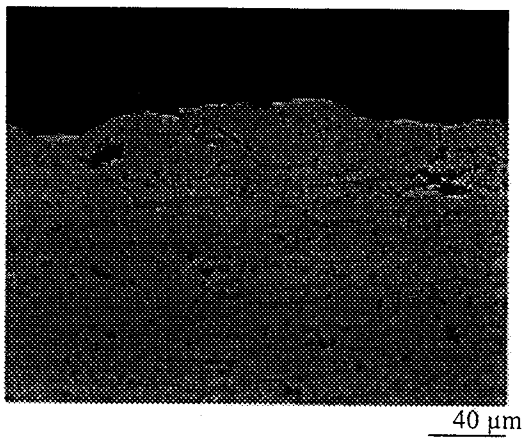


FIGURE 6 - Corrosion pit in LCOR-CX specimen 4.3 mm from the hole after immersion for 4 hours .

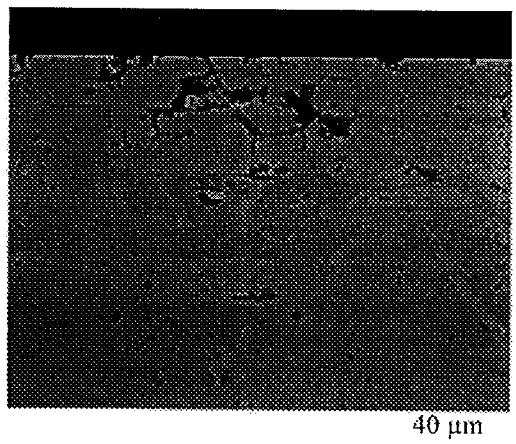


FIGURE 7 – Corrosion pit in COR-CX specimen remote from the hole after immersion for 14 days.

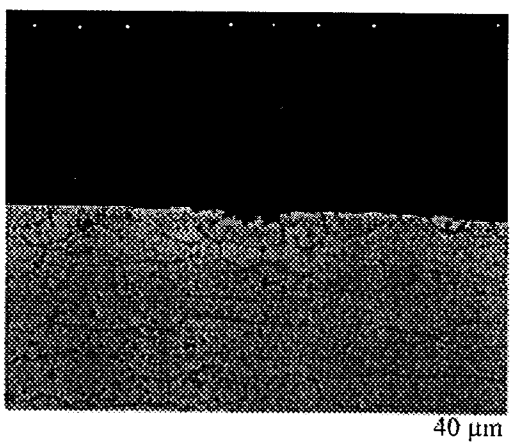


FIGURE 8 – Corrosion pit in CX-COR specimen 9.5 mm from the hole after immersion for 2 hours.

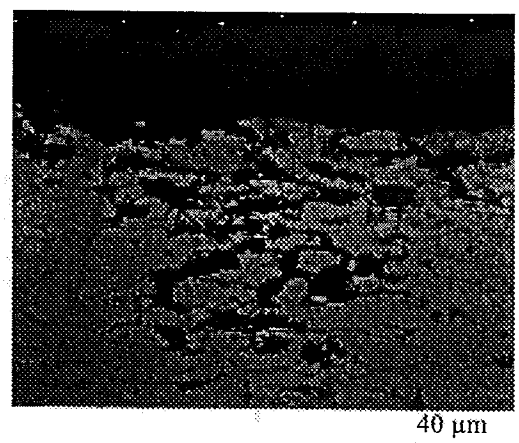


FIGURE 9 - Corrosion pit in CX-COR specimen 16 mm from the hole after immersion of 4 hours.