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AN ARTIFICIAL CORROSION PROTOCOL FOR LAP-SPLICES IN AIRCRAFT SKIN*

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Bevil J. Shaw

Alloy Technology Division
Alcoa Technical Center
Alcoa Center, Pennsylvania 15069-0001

SUMMARY

This paper reviews the progress to date to formulate an Artificial Corrosion Protocol for the Tinker AFB C/KC-135 Corrosion Fatigue Round Robin Test Program. The project has provided new test methods to faithfully reproduce the corrosion damage within a lap-splice by accelerated means, the rationale for a new laboratory test environment and a means for corrosion damage quantification. The approach is pragmatic and the resulting Artificial Corrosion Protocol lays the foundation for future research in the assessment of aerospace alloys. The general means for quantification of corrosion damage has been presented in a form which can be directly applied to structural integrity calculations.

INTRODUCTION

The life extension program for the USAF C/KC-135 fleet necessitates the inclusion of corrosion damage in the life considerations: a factor which previously may have had a minor impact compared with fatigue damage incurred due to flight cycles. The reason for this is that under suitable climatic situations the corrosion damage continues to accumulate irrespective flight time. The program therefore includes, as a major component, the characterization of the effects of corrosion damage on structural integrity and the concomitant changes that may be required in the inspection periods. The damage associated with corrosion can be very important to component life. The damage factors include:

(i) dimensional changes of components which are of two primary types
- change in gauge thickness, due to general corrosion (which results in increased stress);
- localized corrosion (which can act as a microcrack with enhanced local stresses); and

(ii) changes in material mechanical response to loading via
- change in mechanical properties (due to the absorption of hydrogen) and
- change in fatigue crack propagation rates (acceleration by corrosion fatigue).

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Since many aircraft in the fleet were fabricated over 20 years ago, and during the interim period slight modifications and improvements in both compositional range and processing parameters for alloys have been introduced, it is necessary to assess samples of the original material from tear-down aircraft of the aging fleet. These samples have varying degrees of service corrosion damage (natural damage) and can be used directly to assess the related changes in fatigue life. Inspection of the material gathered to date has shown that there may be insufficient samples with significant corrosion damage to provide a reasonable test matrix. Consequently, additional samples are being made by introducing simulated corrosion damage in the laboratory.

The current phase of the USAF C/KC-135 program contains interrelated pilot programs designed to form the framework upon which the new structural integrity issues may be assessed. These include:

(#1) Laboratory Certification for Fracture Mechanics testing,
(#2) Artificial Corrosion Protocol, and
(#3) Test/Evaluation Protocols.

A report on the Test/Evaluation Protocols for Corrosion Damage Assessment (Pilot Program #3) (Ref. 1) was recently issued and it describes the means for optimizing information from a limited matrix of specimens, using a fracture mechanics residual strength model. Pilot Program #2 (Ref. 2), the subject of this paper, is devoted to defining the Artificial Corrosion Protocol, i.e., the means for simulating service corrosion damage in the laboratory. This has to be consistent with the production, within a limited time frame, of a significant number of test specimens to be used in the main component of the fracture mechanics test matrix.

This paper first describes the "natural" damage found in fuselage skin within lap-splices of C/KC-135 aircraft in terms of both the morphology of the damage and the important role of the clad in Alclad skin. The results of corrosion damage produced in C/KC-135 lap-splice samples by three candidate "artificial" laboratory environments are compared with the "natural" corrosion damage and found to be close in appearance. The reasons for long term (up to 60 days) laboratory exposure required to replicate the more severe natural corrosion condition are discussed. Lastly, a general means for quantification of corrosion damage is presented in a form which can be applied parametrically to the structural integrity calculations described in Ref. 1. It should be emphasized that the damage quantification is a most important pivotal issue since it provides the (only) link between NDE (non-destructive evaluation) responses and the damage metrics required for structural integrity calculations and residual life predictions.

NATURAL CORROSION DAMAGE

The term natural corrosion damage is introduced to differentiate the effect of service environments from laboratory environments. The latter is termed "artificial" corrosion damage or "simulated" corrosion damage. This section describes the natural corrosion damage found in samples from fuselage skin lap-splices of C/KC-135 aircraft. It does not include corrosion damage from galley spills (coffee, etc.) or from toilet areas (blue flush, etc.). The general appearance of the damaged skin material and the appearance of corrosion damage in metallographic cross sections are documented. In order to provide a better understanding of the damage process, the results of an experiment which gives a direct observation of the corrosion process in the faying area of a lap-splice are discussed. This information about the evolution and distribution of the corrosion damage is needed to clarify how it should be sampled to provide a meaningful quantification. The natural damage found in fuselage skin of a C/KC-135 aircraft is also analyzed in terms of depth of attack. The terms "Light", "Moderate" and "Severe" corrosion damage are discussed in terms of both the morphology of the damage and the important role of the clad.

General Appearance of Natural Corrosion Damage

The type of corrosion damage found at a lap-splice is exemplified by a "pillowing" or tufting of the outer skin, similar to the tufted appearance of stuffed upholstery. Figure 1 shows a schematic of a lap-splice and how metallographic sections are oriented. Cross sections of the fasteners from lap-splices showed that the tufting effect is caused by corrosion product forcing the skin sheets apart in the presence of fasteners or rivets. It was found that this effect can cause cracking in the rivets. Extreme corrosion damage was also found in the vicinity of spot welds. Damage to the rivets and to welded metal (including the heat-affected zone, HAZ, of the weld) is important but not the primary consideration of this paper.

The corrosion process cannot initiate unless moisture has access to a bare aluminum surface in the faying area. Since the C/KC-135 surfaces are painted and sealed prior to service, the corrosion damage is initiated after the protecting surface has deteriorated. The deterioration is probably a function of paint aging combined with stresses which result from service use and thermal sources (e.g., differential expansion and contraction at a rivet). Inspection of aging aircraft skin structure has shown that crevices in paint are often formed at the fillet and also at the periphery of rivets. Corrosion damage from the crevice around the rivets of a fuselage lap splice *appears* to be somewhat less prevalent than damage from the fillet. Consequently, damage from the fillet is emphasized in this paper.

Natural Corrosion Damage – Light, Moderate and Severe

As part of the Tinker AF project, Boeing-Wichita had characterized the nature and distribution of corrosion damage on a tear-down C/KC-135 aircraft. This natural corrosion damage, which was designated "Light, Moderate and Severe" was approximately characterized by

"light"	"L"	less than 1 mil,
"moderate"	"M"	1 to 10 mils
"severe"	"S"	greater than 10 mils

They found that after stripping the paint, the "M" damage inspected under a high powered (X20) glass appeared as small black specks to the trained eye. Metallographic cross sections of the "L" and "M" conditions were made for evaluation on an IBAS (system for automatic image analysis). The maximum depth for the "L" condition fell between 10 and 25 microns (25 microns is about 1 mil) and the "M" condition had a maximum of 55 microns. It is reasonable that the "M" condition should include "L". It is important to note that the sample of "L" and "M" fuselage skin was Alclad and that the thickness of the clad was 60 ± 10 microns. An inspection of over 30 one-inch-long sections of this sample of "L" and "M" damage showed that it all was within the clad. Further evaluations of 7075-T6 and 2024-T3 lap-splice samples from a C/KC-135 had similar characteristics.

In the course of the inspection of *cross sections* of corroded specimens, it became apparent that the distribution of the corrosion damage, as a function of distance from the fillet of the lap splice, was quite irregular. For example, proceeding from a heavily corroded section adjacent to the fillet, one might find a section of no corrosion followed again by heavy corrosion. In other words, the corrosion damage, judged by depth or area in the cross section, was not a simple decreasing function of the distance from the fillet.

A number of lap-splices were taken apart and it was found that the faying surface of the inner skin was not painted. This suggests that the skin is undercoated on the inner surface prior to construction and the outer surface is painted after construction. The one residual bare aluminum surface in the faying area often appears to be chemically treated, e.g., with Alodine, but it is also the preferentially attacked surface since it is not painted.

Plexiglas Simulation Experiment

In order to observe the corrosion phenomenon in the faying area, a simulation lap splice was made in which the outer, completely painted skin surface was replaced with a sheet of Plexiglas attached to an Alclad sheet by nylon bolts. The specimens were stood upright so that the fillet was just immersed in a solution (EXCO (Ref. 3) to which hydrogen peroxide (H_2O_2) was added at the rate of 10 ml/litre/day.) which was drawn up into the faying area by capillary action. Moisture entry in service must be somewhat similar to this process. The faying areas of the simulation lap-splices had a similar appearance to that of the service specimens. Inspection on daily intervals showed that the solution was not drawn uniformly into the crevice and that the distribution of corroded surface was correspondingly irregular. The total corroded area also varied discontinuously with time, probably because the corrosion product filling the crevice gradually lifted the Plexiglas until the condition for further solution penetration into the faying area was created.

In the simulation experiment it was observed that the paint adjacent to the fillet (equivalent to the outside skin surface) was lifted from the aluminum surface. In the service situation, the degraded paint surface would be repaired by paint removal and repainting. This procedure will serve to introduce paint in the fillet (a paint wedge which can be 10 mils thick) in so far as the corrosion product has not been removed. There are important consequences to this situation since the resulting configuration, with substantial new paint included in the fillet compared with none previously, will provide *additional protection* to the faying area. The additional time required to reactivate corrosion process within the faying area will be as long as it takes either to undermine the paint wedge or to penetrate the area from the side. It is evident from this discussion that a lap-splice which *appears* to be unaffected by corrosion may and often does contain *occluded* corrosion damage if it has been repainted.

Discussion of the Role of the Clad

Alclad sheet product has been employed in aircraft construction for corrosion resistance and strength retention characteristics since 1928. The clad, typically 1 to 10% of the thickness of the sheet (i.e., usually in the range 1 to 3.5 mils or 25 to 90 microns) is metallurgically bonded to the core (Ref. 4). There are two stages to the protection. First, the clad itself is more resistant to corrosion than the core. Secondly, since the clad is also anodic to the core, it provides electrochemical protection of the core. If a corrosive solution is in contact with both the core and the clad, current from the anodic cladding flows through the electrolyte to the core which is then protected since the clad tends to dissolve. This protection depends upon conductivity in the electrolyte.

In the faying area of the lap-splice, moisture (rainwater) containing environmental pollutants (NaCl, H_2SO_4, etc.) is probably introduced by capillary action. Once a crevice has formed in the protective paint at a fillet, the clad in the faying area (not in contact via an electrolyte to the core in the initial stage) can be corroded by the moisture. When contact via the electrolyte has been made with the core, the primary corrosive action will be the dissolution of the clad. This contact may be made by attack through the clad or from within a hole for a fastener or rivet in the skin. Normally, this stage provides protection for a very long time. Consequently, it is commonly observed that the faying surfaces of a lap-splice, which has been taken apart, are covered with (a white) corrosion product which very often does not penetrate the core. Penetration is achieved in circumstances where contact between the clad and core has been lost or the "throwing power" (Ref. 5) is limited by distance between the clad and core.

From the mechanistic point of view there are three stages of corrosion damage to the skin.

(i) Pitting of the clad, which can be loosely associated with the light, "L", condition of attack less than 1 mil.

(ii) More general dissolution of the clad, resulting from the electrochemical protection. Provided the clad is greater that 1 mil thick, which it usually is, this stage falls in the moderate attack, "M", condition.

(iii) Attack beyond the clad into the core of the skin. This stage can fall within the "M" or "S", severe, condition. Note that the attack of the core can and often does include intergranular cracks and (equivalently) exfoliation crevices.

ARTIFICIAL CORROSION DAMAGE

This section provides a review of results from corrosion in laboratory environments, termed artificial or simulated corrosion damage. The primary emphasis has been on the replication of the corrosion damage found in the skin due to natural environments. The program required the development of a protocol for the simulation of severe "S" corrosion damage in as short a time as possible. All of the C/KC-135 fuselage lap-splices samples received for the study were Alclad on both faces except for one sheet of one lap-splice which was clad on one face only. This was one of the painted surfaces in the faying area and so it was relatively free from attack. Consequently, the discussion of the role of the Alclad given in the previous section pertains to the artificial corrosion study. Procedural rules for the corrosion protocol included the requirement to make the method as close to the natural process as possible. Thus, lap-splice specimens were cut from a dismantled C/KC-135 aircraft and tested without modification except that the paint at the fillet could be broken by local impact.

Corrosion in the Faying Area of the Lap-Splice – Environments

In the service situation moisture will be retained within the faying area crevice while the outside of the aircraft can be dry. This extended moisture period should be examined, possibly by use of specimens with a Plexiglas face, in order to determine a relationship between the service experience and the laboratory test. The following example gives an idea of the order of magnitude involved. A lap-slice which had been tested in EXCO was dismantled to expose to air the moist corrosion product on the faying surfaces. Under an orthoscope it was observed that hydrogen was evolving from the corroded surface and continued to evolve for five days. The relative humidity was not high, between 40 to 50%, for the entire period. Clearly, the faying area of the lap-splice would have retained moisture for a longer period.

In a series of experiments on a separate Alcoa project, it was demonstrated that the most degrading condition in the Alternate Immersion (AI) test (Ref. 6) is towards the end of the drying cycle. It was also shown that this condition was related to oxygen content of the solution and that it could be replicated by the addition of H_2O_2. Similarly, Ishihara et al. (Ref. 7) demonstrated that fatigue crack growth is strongly influenced by the transport of oxygen to the solution localized at the tip of the crack. In fact, one of the ASTM standard methods, G 110- 92 (Ref. 8), for evaluating intergranular corrosion resistance of heat treatable aluminum alloys employs a NaCl + H_2O_2 solution. The blending of this method with the EXCO method therefore appears to be a logical way of accelerating the attack. Oxygen reduction on the metal outside the crevice, especially because the area of exposed metal outside the crevice is small, is a rate limiting factor for the crevice corrosion. Hence, the addition of the H_2O_2 to the solution optimizes the crevice corrosion process.

It is known that adjacent to a crack tip the pH will increase to a value of 3 to 4, due to "buffering" or the dissolution of A (Refs. 9, 10). In fact, the pH within a crack has been found to be relatively insensitiv to the pH of the solution. Within the faying area crevice the conditions will be similar. In the EXCO or EXCO + H_2O_2 test, the corrosion rate is slower within the crevice than on the outer surface where the pH is maintained at .5 to 1.5. It follows that whereas the experimental condition may be similar to service conditions for the faying area, they are quite different on the outer surface. In the experimental condition part of the sample is immersed in the solution whereas in service the skin is in air. For this reason particular care has to be taken to seal the specimen outside of the crevice at the fillet.

Returning again to the requirement that the laboratory process should closely replicate the natural environment, it is evident that whereas EXCO and EXCO + H_2O_2 replicates the corrosion damage *appearance* of heat treatable aluminum alloys, the EXCO solution bears little resemblance to the rainwate which would be found around the world in service situations. It might be considered to be representative of sea-board or marine spray, but S. B. Lyon et al. (Ref. 11) state that this kind of test environment is not appropriate for atmospheric corrosion testing since there is little similarity to naturally occurring rainfall and the corrosion products could be different from those produced during natural weathering. Certainly, EXCO contains no H_2SO_4 and almost invariably sulfur is found in natural corrosion products produced b rain. The composition and pH of the "artificial acid rain" (AR) solution provided by S. B. Lyon et al., compared with EXCO is shown in Table 1.

An experiment was carried out to compare the relative attack caused by AR and EXCO, with and without H_2O_2, on the bare surface of a 7146-T6 alloy which is used as an exfoliation standard. The corrosion damage is enhanced by the H_2O_2 and the EXCO is considerably more aggressive than the artificial rain but the metallographic cross sections of the specimens all show similar exfoliation corrosio characteristics. Since the EXCO is far removed from the natural acid rainwater composition and the "artificial acid rain", even with H_2O_2, is not very aggressive, it was decided to employ a more concentrat composition of AR which approximates to a log mean between AR and EXCO. The composition and pH of the "concentrated artificial acid rain" (ARX) are given in Table 1. AR and ARX have pH values less than will be expected within the crevice but they will not lift paint from the skin surface quite as aggressively as EXCO. The relative performance of the three solutions, EXCO, AR and ARX with H_2O_2 addition is given in the next section.

Corrosion in the Faying Area of the Lap-Splice – Corrosion Rates

Lap-splice specimens from a tear down C/KC-135 aircraft of Type #1 (7075-T6) and Type #3 (2024-T3) were used for the primary experiments. All areas except the cracked paint at the fillet were sealed with Finch primer or RTV. The specimens were stood upright so that the fillet was just immersed in the solution which was drawn up into the faying area by capillary action. The specimens were tested in the three solutions listed in Table 1. It was established that 15 day intervals would be sufficient to adequatel follow the damage evolution in the faying area. In the initial experiments metallographic sections were taken perpendicular to the fillet (i.e., perpendicular to the line A-A in Figure 1) with a view to measuring the "damage" along this length to represent the effect of distance from the fillet. However, it was subsequently found that the damage is not a uniform function of distance from the fillet and hence, for the 30 and 45 day analyses sections were taken as indicated in Figure 1. After metallographic sectioning, statistics of the corrosion damage were gathered on the IBAS (system for automatic image analysis).

The IBAS stores a representation of the image on its computer and hence allows for image enhancement and rapid quantification of features depicted via pixels on the monitor screen. Figure 2 shows a typical (IBAS image enhanced) metallographic section from corrosion damaged faying area with light "L" and moderate "M" damage characteristics. The appearance of the natural corrosion damage (Ref. 2) is the same as the artificial corrosion shown in these figures. The IBAS data gathered from the damaged skin cross sections was:

(i) The maximum depth of the damage, $d_{(max)}$, within a given field of analysis (L_f)
(ii) The total area of the damage (ΣA) within a given field of analysis (L_f).
(iii) The total surface length of damage, (ΣL) within a given field of analysis (L_f).

where L_f is the length of the cross section of the skin which has been analyzed at a given location. These data are sufficient to characterize the corrosion damage for the Artificial Corrosion Protocol purposes. The acuity (or sharpness quantified in degrees) of pits or crevices can also be readily determined on the IBAS. However, important as acuity may be to the life prediction (local stress enhancement leading to reduced time for crack initiation) it was not included in the current study which is designed to introduce the damage. The data package generated for the test matrix contained four primary variables as follows:

(i) specimen type	Type #1, Type #3 (7075-T6, 2024-T3)
(ii) location (distance, Y, from fillet)	0.25 inch intervals to 2 inches Y0, Y1, Y2,...Y_n..
(iii) solution	EX, ARX and AR.
(iv) time	0, 15, 30 and 45 days

From the above data set, representations of damage distribution, both for exposure time and location, can be graphically depicted provided a metric of damage is defined. For a skin section, the "loss of area" is the change in thickness of the skin times the length of skin section under load. Consequently, thickness or change in thickness is the required metric. Non-uniform loss due to corrosion damage raises interesting questions for the definition of the term "equivalent loss of area". At one extreme there is the *local* thickness (which in fact could include acuity, for which one may attribute an equivalent flaw) and at the other extreme the *average* thickness. The two measures of the skin damage (which are estimates of the change in thickness of the skin) may be regarded as approximations to an upper bound and a lower bound to the loss of area.

For the upper bound, a (first) approximation is the "average maximum pit depth" (i.e., average of $d_{(max)}$) in each location (Y). This is proportional to the maximum depth of the corrosion damage across the faying area in each location. The actual maximum depth can be estimated from application of extreme statistics to the maximum depth distribution. For the lower bound, a (second) approximation is the "average depth of attack" of the skin in each location (Y). This is the total area of the damage divided by the total surface length of damage within the field of analysis in each location (Y) or $[\Sigma A/\Sigma L]_Y$.

The approximation for "equivalent loss of area" is not limited to these two estimates. The upper extreme bound could be represented by some change in thickness which takes into account the extreme maximum pit depth and an equivalent flaw factor associated with acuity. The lowest extreme bound would be represented by an "average thickness loss" of the skin which is the total area of damage divided by the surface length in the field of analysis in each location (Y) or $[\Sigma A/Lf]_Y$. Examples of distributions of the "loss of area" approximated by the "average maximum pit depth" - as a slightly low estimate for the upper bound - and "average depth of attack" - as a lower bound - may be represented graphically .

In this paper one example, Fig. 3, showing the effect of the test solutions and time at the fillet (Y=0) and another, Fig. 4, showing the effect of time and distance from the fillet ($Y=Y_n$) on the average maximum pit depth serve to represent the general trends found in the experiments. (See Ref. 2 for more detailed treatments.) In general, the corrosion damage rate for EX>ARX>AR, though ARX and AR are not as clearly separated as EX and ARX. Note that the zero day damage is the natural damage found in the "as-received" condition. The effect of time and distance from the fillet on the average maximum pit depth shows the expected trends that

(i) damage penetration from the fillet increases with time
(ii) the depth of corrosion damage at a given time (pitting or clad dissolution) is reduced with distance from the fillet and
(iii) damage tends to be greater in Type #1 (7075-T6) than Type #3 (2024-T3).

Figures 3 and 4 show that in the AR environment the damage barely exceeds the depth of the clad within the faying area whereas the penetration of damage beyond the clad is significant in both ARX and EXCO.

The clad alloys for 7075 and 2024 are 7072 and 1230, respectively. Typically, the 7072 is less resistant to corrosion than 1230. However, with no clad, 7075-T6 is more resistant to corrosion than 2024-T3. It follows then that the initial "damage" in terms dissolution of the clad will proceed faster in the 7075-T6 samples. Most importantly, the undercutting of the paint immediately adjacent to the fillet is lifted faster in 7075-T6 than 2024-T3 samples. Also, our observations of the rate of paint undercutting are EX>ARX>AR as expected. Since the corrosion rate in the faying area increases with the uncovered metal immediately outside the fillet (Ref. 12), the initial crevice corrosion rate within the clad should be faster in Type #1 than Type #3 for both reasons (clad resistance and undercutting rate).

Referring again to the Plexiglas experiment described above, it was found that a "Heavy" corrosion product adjacent to the Plexiglas of the simulation lap-splice experiment fillet was equivalent to "M" corrosion within the clad. The rate of growth of the "M" corrosion attack perpendicular to the fillet is approximately 0.8 to 1 mm per day (about 1-1.25 inches per month) in the 2024-T3 specimen. The average penetration of "M" corrosion in the 7075-T6 specimen was difficult to measure, because the interface with lighter corrosion was obscure, but it appeared to have a slightly faster growth rate.

The Plexiglas simulation experiment can be compared with the artificial corrosion experiment. Figure 4 shows that the moderate damage condition for the Alclad 2024-T3 in the EXCO test is found approximately 0.5 in from the fillet after 30 days and 1.25 inches after 45 days, i.e., a rate of 0.5 to 0.8 inch per month. This is in reasonable agreement with the observed Plexiglas experiment rate of about 1 inch per month, considering that the Plexiglas should be lifted more readily by the accumulated corrosion product than aluminum. The corresponding rate for the Alclad 7075-T6 in the EXCO test, Figure 4, is about 1.25 inch per month.

DISCUSSION AND CONCLUSIONS

The experiments have shown that initially an aggressive environment (e.g. EXCO) has to be used to lift the paint and dissolve the clad adjacent to the fillet within a short time (i.e. days). In this stage, (i) corrosion damage will extend from the fillet crevice both into the faying area and under the adjacent exterior paint, and (ii) all surfaces except the paint crevice at the fillet must be carefully protected in order to limit specimen surface degradation. The artificial acid rain solution (AR) is not sufficiently aggressive for this stage. Since the solution in the faying area is "buffered", the subsequent corrosion rate within the faying area is probably similar for the three test solutions evaluated. The corrosion rate in the faying area should increase with uncovered metal immediately outside the fillet. As a result of these considerations, the damage should be introduced in two stages.

(1) Rapidly undercut the paint outside the fillet with an aggressive environment, e.g., EXCO + H_2O_2.
(2) Maintain an optimum crevice corrosion condition which limits rapid attack outside the fillet. This can be achieved by alternate immersion in AR or ARX + H_2O_2 in which the crevice retains moisture. The composition of the second stage environment is a concentrated rain which is representative of the natural environment.

Since the paint lifting from the specimen surface in stage (1) will be a function of the Alclad alloy and the quality and type of paint, the metal surface area in contact with the solution will be an (uncontrollable) function of time. This means that for a given time of exposure to the EXCO solution, the amount of damage for one sample will not necessarily be the same as for another. It follows that each batch of material should be processed independently to produce the same amount of corrosion damage.

The quantification of corrosion damage is discussed only from the point of view of geometric change and does not include important considerations such as crack growth in the presence of a corroding environment (corrosion-fatigue) or the role of absorbed hydrogen on crack initiation or propagation. The mechanistic point of view indicates three stages of corrosion damage to the skin:

(i) Pitting of the clad, which can be loosely associated with the light, "L", condition of attack less than 1 mil.
(ii) More general dissolution of the clad, resulting from the electrochemical protection. Provided the clad is greater that 1 mil thick, which it usually is, this stage falls in the moderate attack, "M", condition.
(iii) Attack beyond the clad into the core of the skin. This stage can fall within the "M" or "S", severe, condition. From this viewpoint it would be simpler to define "M" as stage (ii) i.e. greater than 1 mil and within the clad and "S" as attack extending into the core, i.e. greater than 2 to 3 mils.

Quantification of the corrosion damage is required for life analysis methodologies and structural integrity calculations. The simplest model should consist of two parameters which may be determined from metallographic cross sections:

(i) Loss in thickness of the skin which is directly related to the "loss of area" is discussed and

(ii) An "equivalent flaw" component which represents pits, intergranular cracking or exfoliation crevices in excess of the average loss in area.

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Table 1. Compositions of EXCO, Concentrated Acid Rain and Artificial Acid Rain. Laboratory tests were carried out in these solutions with the addition of 10 ml/litre/day of H_2O_2.

Solution Concentrations [per litre]			
	(1) EXCO	(2) Concentrated Acid Rain	(3) Artificial Acid Rain*
NaCl	234 g	5 g	0.085 g
KNO_3	50 g	—	—
HNO_3	6.3 ml	0.25 ml	16 mg
H_2SO_4	—	0.5 ml	32 mg
$(HN_4)_2SO_4$	—	1500 mg	46 mg
Na_2SO_4	—	1000 mg	32 mg
$NaNO_3$	—	750 mg	21 mg
pH	~0.6	~2	~3

* Ten times average concentration in Greater Manchester [U.K.] in 1986. (Industrial Environment)

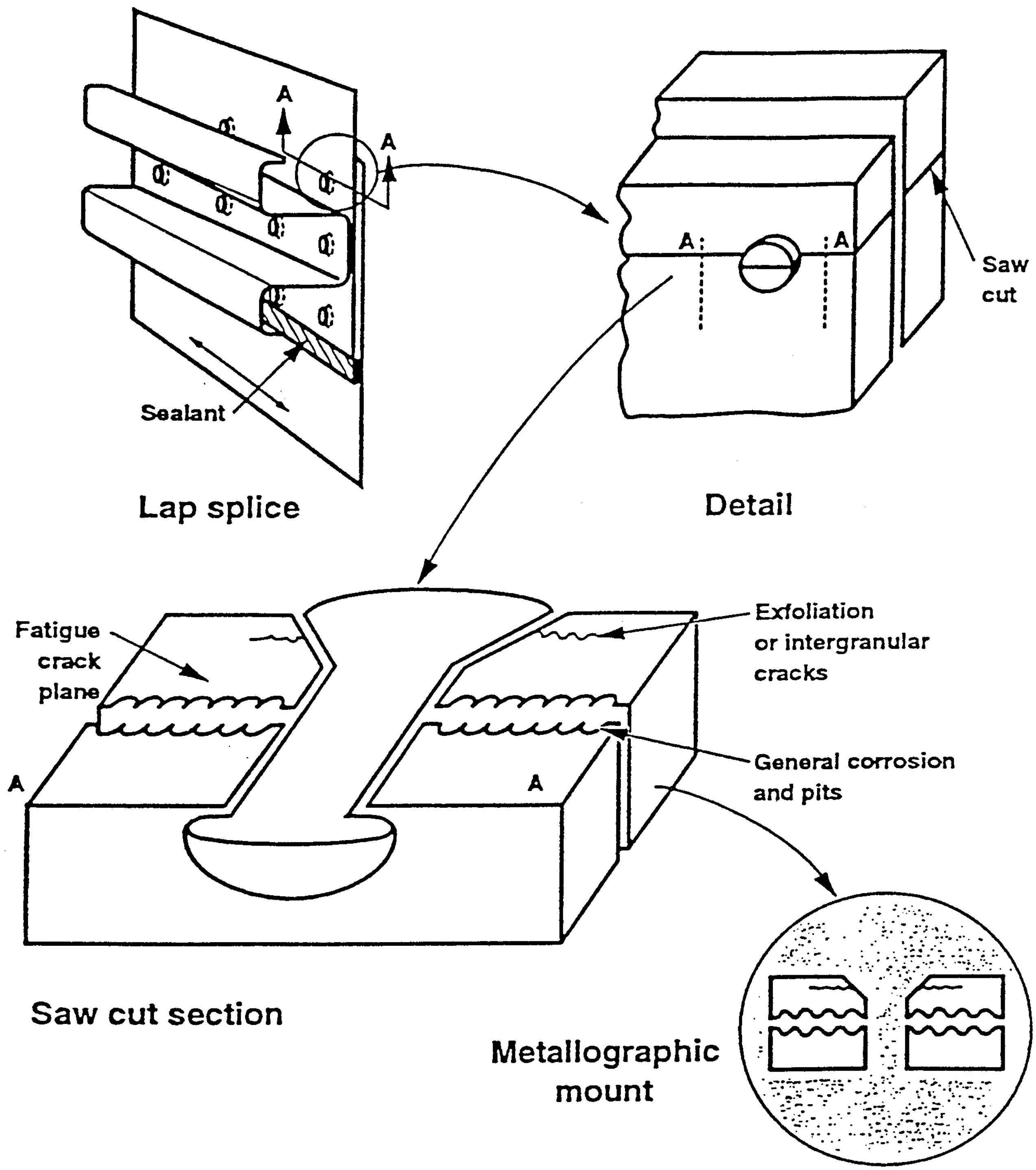
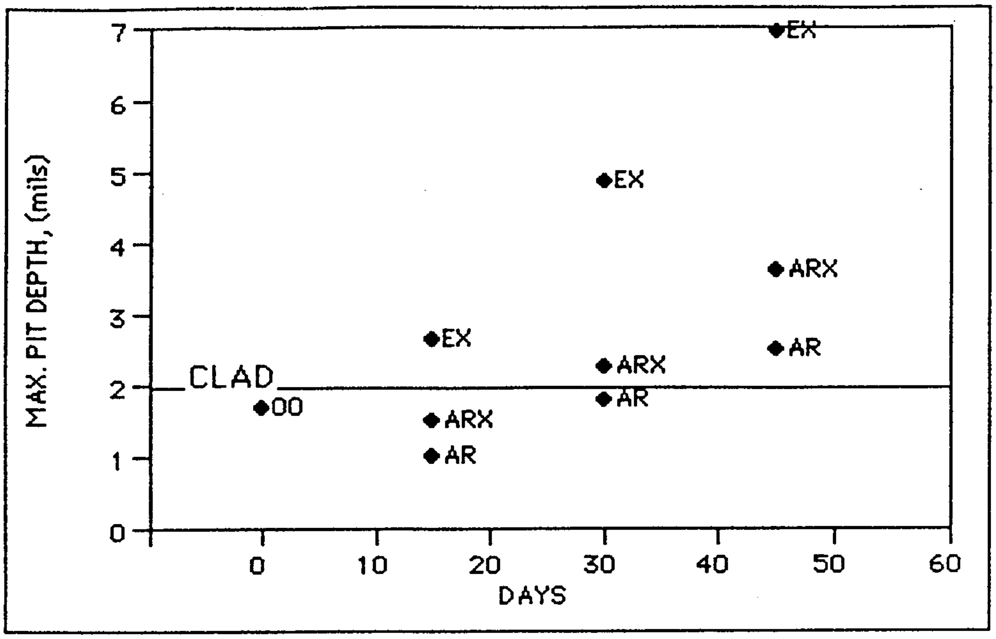
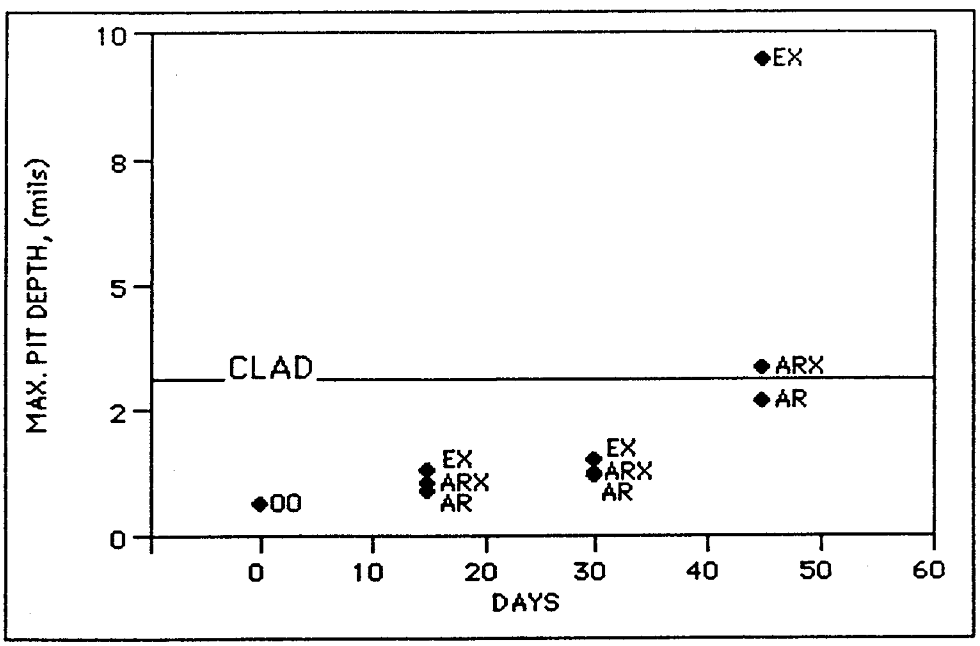


Figure 1. A schematic of a lap-splice showing how metallographic sections are oriented.

Figure 2. Image analyser micrograph showing (a) light (L) and (b) moderate attack (M) of the joint faying area made from 2024-T3 Alclad sheet. The clad layer is the lighter structure at the top of the micrograph, about three mills thick. The white line at the top of the micrograph shows the original location of the clad surface. The quantitative measurements include the area loss within the length of a cross section and the average and maximum depth of penetration. Magnification X500.

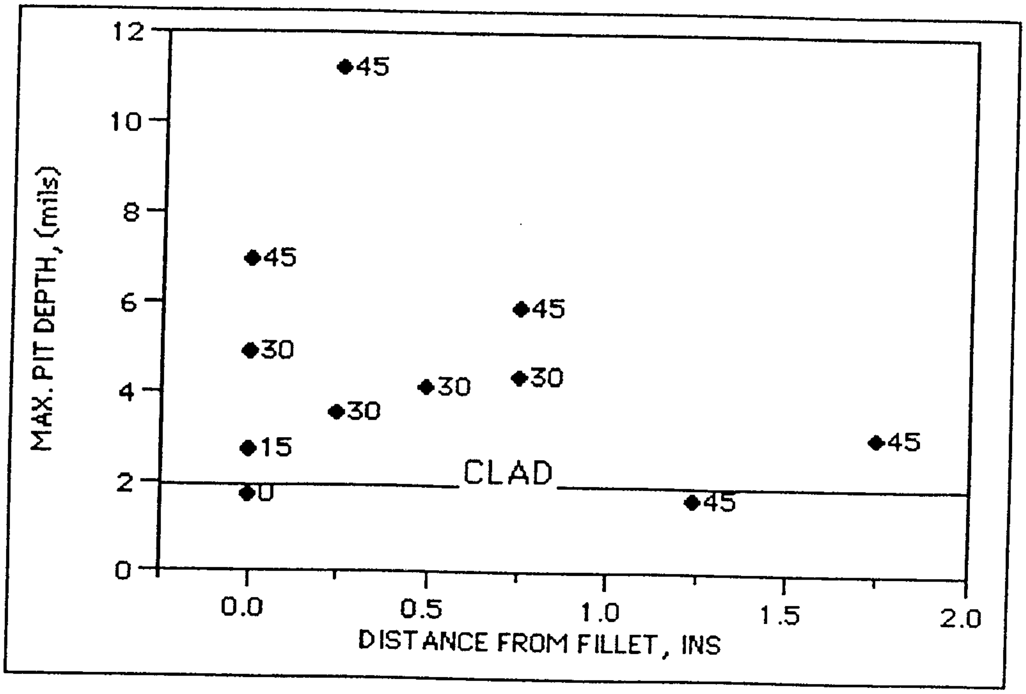


7075-T6 AT FILLET

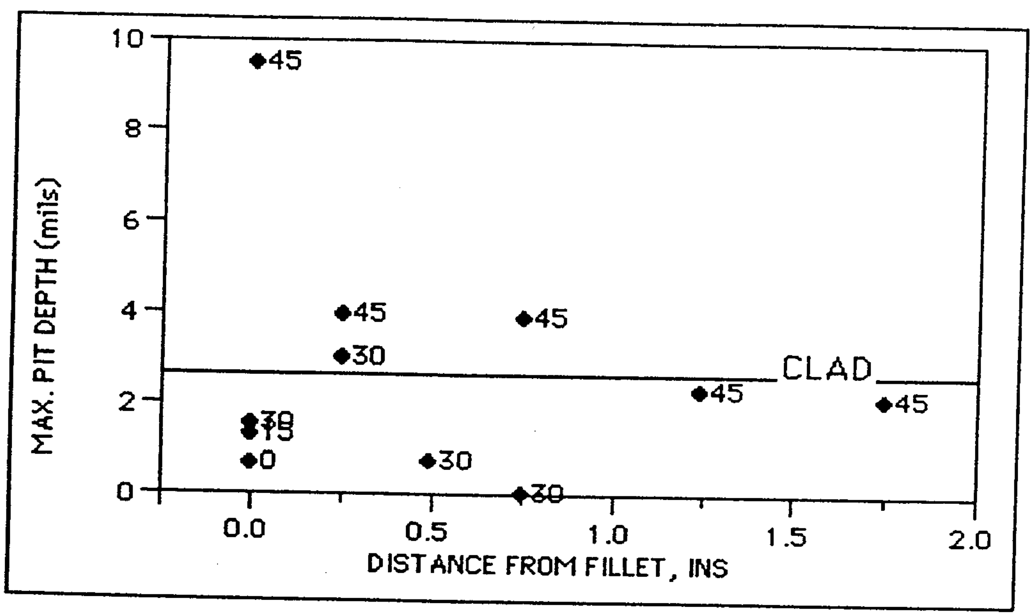


2024-T3 AT FILLET

Figure 3. The average maximum pit depth at the fillet for Type #1 (Alclad 7075-T6) and Type #3 (Alclad 2024-T3) lap-splices as a function of the number of days exposure . The test solutions are indicated by AR, artificial acid rain + H_2O_2, ARX, concentrated artificial acid rain + H_2O_2 and EX, EXCO + H_2O_2.



7075-T6 IN EXCO



2024-T3 IN EXCO

Figure 4. The average maximum pit depth resulting from exposure to EXCO+ H_2O_2 solution as a function of the distance from the fillet for Type #1 (Alclad 7075-T6) and Type #3 (Alclad 2024-T3) lap-splices. The number of days exposure is indicated adjacent to each point.