CORROSION FATIGUE - THE FORGOTTEN FACTOR IN ASSESSING DURABILITY

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INTRODUCTION

After more than 60 years of research [1, 2], corrosion fatigue still presents a very diffuse picture. Widely different conclusions about the effect of corrosion on fatigue strength can be drawn from the literature, from „disastrous" [3] to „negligible" [4] or even „beneficial" [5]. The reason is clear: On the large number of parameters influencing fatigue strength, see Fig. 1, another large number of corrosion parameters is superimposed; what is more, they are superimposed in a synergistic manner; that is, their effects cannot simply be added; rather, they act together in a very unclear way.

Also, things one can do with impunity in normal laboratory fatigue tests, for example increasing the test frequency compared to actual service, may not be correct in laboratory corrosion fatigue tests. Another difficulty is that while fatigue-tests or -calculations result in numbers (i.e. cycles to failure), albeit sometimes incorrect ones in calculations, corrosion tests do not. Numbers given in this respect, i.e. "mass loss per m^2 per year" are not a good measure of the damage done. Even if they were, such numbers would be incompatible with the numerical results of fatigue tests.

To add to the confusion, materials which withstand normal corrosion very well, like stainless steels or the so-called "marine" aluminium alloys, show no similar resistance, if in addition cyclic stresses occur, i.e. corrosion always is detrimental to fatigue strength, at least in some aspects, for example in the welded condition, or in the crack propagation phase. Also, different types of loading, i.e. constant or variable amplitudes can result in even qualitatively wrong answers etc. etc.

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In addition - at least in the opinion of the author - researchers have placed too much emphasis on the electrochemical reactions between the corrosion agent and the material of unnotched specimens (or at the crack tip of cracked specimens), while the corrosion fatigue performance of actual components and structures up to now has almost been neglected: Therefore, out of the huge number of papers on the subject of corrosion fatigue, only a small amount is available for answering that most important engineering question: "What will the probable behaviour of our structure be in actual service under corrosion fatigue conditions?"

The present paper is an attempt to answer this question, based on some corrosion fatigue test programmes, not all of them with aircraft materials*; it will also try to draw some general conclusions on the effect of corrosion on fatigue which have almost been missing up to now.

Finally, some suggestions for further work and for the carrying out of corrosion fatigue tests are made.

LABORATORY TESTS AND SERVICE BEHAVIOUR

If a normal fatigue test in the laboratory simulates the service conditions well, we are reasonably sure it will give similar results to service, viz. the results of full scale fatigue tests on aircraft.

However, this cannot be said for corrosion fatigue tests. One reason certainly is the added complication due to the corrosive medium, i.e. the effect of test frequency, time in the medium, type of medium etc. etc., in the laboratory test. Very complex events happen even in a simple corrosion fatigue test. Consider a notched or cracked specimen: Corrosion fatigue takes place at an extremely local area or section, while corrosion acts on the whole surface. So there must be a sudden "jump" from corrosion to corrosion fatigue near the fatigue critical location.

Even more complex - and that is another reason for our difficulties with corrosion fatigue - is the difference between a corrosion fatigue test on a structure in the laboratory - even with

* A surprising number of similarities exist with regard to corrosion fatigue effects on widely different materials, for example on the effect of test frequency, test duration etc.

the best simulation possible - and the corrosion fatigue behaviour of that structure in service. The author has attempted to describe this in Fig. 2: The main difference is that in service the component or structure is being "corrosion fatigued" only during a part of the life - in tactical aircraft with 150 flying hours per year only during a very small part, less than 2% - while it is presumably being corroded all of the time, at least if the corrosion protection scheme has broken down. In the laboratory, however, the component is usually being corroded and "corrosion fatigued" all of the time.

If such a fatigue loaded component fails in service after 20 years, can we really say with confidence the cause was corrosion fatigue? One can even visualise a corrosion fatigue - loaded thin-gauge component which fails in service outside the fatigue-critical section by just corroding away, although the cyclic loads in a laboratory corrosion fatigue test would have failed it by fatigue long before.

The addition of a corrosion protection scheme completely changes the picture. As long as it is not breached, neither corrosion nor corrosion fatigue occurs, only fatigue remains and the component will fail in the fatigue critical section. If the c.p. is breached at the fatigue critical location (due to the higher strains there, for example) only corrosion fatigue occurs. Conversely, if the c.p. is breached due to damage outside the fatigue critical section, there will be a competition between corrosion there and fatigue at the corrosion protected, but fatigue critical section.

Other differences between the usual corrosion fatigue tests, with - at best - notched or cracked specimens and the behaviour of real structures are that crevice corrosion and galvanic corrosion can occur in service, which may increase the deleterious effect of corrosion on fatigue life. Even if real components are tested in the laboratory, the much shorter testing times and higher frequencies compared to service may result in different results. At high frequencies, for example, the medium may be pumped into and out of a crack at every cycle [10], while in service it remains (for 98% of the time!) in the crack, changes it's p.h. - value, etc.

It is clearly impossible to exactly simulate these complex events in a normal fatigue test in the laboratory; in fact, in the overwhelming majority of corrosion fatigue tests, none of the service corrosion parameters is simulated correctly, see Fig. 2.

In many laboratory corrosion fatigue tests, extremely detrimental effects of corrosion are found, see below. Had these been acting to a similar degree in actual service, many structures from ships and oilrigs to automobiles and aircraft would have failed by corrosion fatigue long ago. Probably this difference is partly due to too severe corrosion conditions in the test, but mostly due to the selection of incorrect test specimens.

THE EFFECT OF CORROSION ON FATIGUE LIFE

General Remarks. As briefly mentioned in the introduction, the effect of corrosion on fatigue life or -strength at first sight looks very confusing, ranging from „catastrophic“ to „negligible“ or even „beneficial“, at least as judged from laboratory tests.

A closer look, however, shows that the results of these laboratory tests depend on their parameters - as is usual for fatigue tests in air. In corrosion fatigue tests, there are many additional parameters, therefore one must look even closer at the details of the tests.

This look is complicated by the fact that fatigue engineers have to „unlearn“ some facts they know, for example:

- The „size“ effect, (large specimens have a shorter life than small ones) is reversed [9] in corrosion fatigue.
- Coatings (anodising, chromium plating, cladding etc.) which are detrimental to fatigue in air, are beneficial in corrosion fatigue.
- Tensile overloads prolong fatigue life in air, but may shorten it in a corrosive medium if they crack the corrosion protection scheme or loosen rivets.
- „Wet assembly“ or water displacing fluids will usually shorten fatigue life in air, but will prolong it in a corrosive medium.
- etc. etc.

There are other „facts“ about corrosion fatigue which engineers only think they know, for example:

- „Corrosion takes a long time to have effect on fatigue life“; as will be shown below, such an effect can often be found after a few minutes in the medium.
- „The lower the test frequency (and therefore, at the same stress amplitude, the longer the test duration), the higher will

be the corrosive effect on fatigue life": Many materials do not show a frequency effect, see below
- „Higher stress amplitudes and therefore shorter times in the environment will result in less corrosion fatigue damage": High amplitudes may loosen rivets or damage the corrosion protection, resulting in a relatively shorter corrosion fatigue life.
- „Cathodic protection always will be beneficial": It may even be detrimental for fatigue crack propagation.
- „A corrosion resistant material will be good in corrosion fatigue": All corrosion resistant structural materials show large corrosive effects on fatigue life in the unnotched state, others also in the notched condition, still others in crack propagation. Good corrosion fatigue properties in the notched condition mean just that, but no more, the same material may be very critical in corrosion fatigue crack propagation. Even within one type of corrosion fatigue test, the behaviour of a material may be very different from that in air: ΔK_{th} in air may be lower than ΔK_{th} in seawater, for example, while at medium ΔK the crack propagation in air may be much slower, near K_c both crack propagation curves being very similar.
- „The effect of the environment on fatigue life can be judged (or even calculated) from constant amplitude tests": Not if the stress amplitudes in service are variable, see below.
- etc. etc.

Some of the effects mentioned above will now be discussed, based on a number of corrosion fatigue test programmes (not all of them with aircraft materials)

Time Effects On Corrosion Fatigue. Many corrosion fatigue tests concerned the effect of time in the environment, of test frequency etc. and widely different results were obtained. An example where test frequency had no statistically significant effect is shown in Fig. 3: Although the test frequency varied between 0,2 and 10 Hz, the numbers of cycles to failure were practically identical [27]. Similar welded specimens with artificial crack starters, however, showed a large effect of test frequency [45]. The conclusion therefore was that the original specimens, although welded, had a long crack initiation, but a short crack propagation life.

A similarly small effect was found in the simultaneous program in the U.K. [28] see Fig. 4: In variable amplitude tests the

S-N curves in seawater and air were parallel. At the test frequency employed of 0,16 Hz this is shown to be so for up to about 200 days ($2 \cdot 10^6$ cycles). No tests at other frequencies were caried out. However, since the overall effect of corrosion was small even at 0,16 Hz, it must be concluded that higher frequencies would have had a similar or an even smaller effect.

Helms and Henke in [29] investigated the frequency effect down to 0,01 Hz. For the structural steels of this programme the fatigue life in artificial seawater decreased by a factor of slightly less than two (welded specimens) and slightly more than two (plain specimens), if the frequency was lowered by a factor of one thousand! The time in the environment therefore was higher by a factor of about 500, the longest test lasted about 500 days.

Corrosion fatigue tests on similar specimens with hold times of one second in the tensile as well as the compressive part of a trapezoidal cycle were carried out by the author [30] in connection with the standardized load sequence "Wash" [31]: No statistically significant influence of these dwell times compared to 10 Hz sinusoidal amplitudes was found. All SN-curves including that in air also were parallel, at least in the finite life region up to 10^6 cycles, indicating that time in the environment was not an important parameter.

In [8] Kemp showed the influence of testing frequency for 7010 - T7451, reaching a maximum factor of 8 between 15 and 130 Hz, see Fig. 5. The effect on 7010 - T7651 was nil, although this is difficult to understand, because the two materials only differ in heattreatment.

From Fig. 6, taken from [32], another typical effect can be learned: After very short testing times, a detrimental effect of the corrosive environment will occur, viz. the curves for L97, 7010 - 7651 and L93, the fatigue strength of which had decreased to less than 80% of the air value after only 13 minutes (= 10^5 cycles at 130 Hz) in the medium *. Similar results were obtained by the author [33] with an amagnetic stainless steel: Longitudinal stiffener welded specimens showed a detrimental effect after only $2 \cdot 10^5$

* The other data shown in Fig. 6 are difficult to believe (corrosion fatigue life higher than in air, frequency effects reversed, etc.) and are probaby due to sçatter, different batches of material etc.

cycles (= 33 min at 125 Hz). Also, no effect of testing frequency was found between 5 Hz and 125 Hz.

In view of these and many other results it is difficult to visualize any pitting taking place after so short a time [34, 35]. In fact, it is even more difficult to believe in the firmly established phrase "Corrosion is a time-dependent process". Can we really say this for corrosion-fatigue?

Conversely, if a corrosion pit was the origin of a service fatigue failure, any corrosion fatigue test which did not likewise produce pits obviously was not a correct simulation of service, whatever the reason.

Another heretical question comes to mind: What was the effect of testing frequency in air? Had it been as big as in the corrosive medium, this could only mean that air was also corrosive or that the frequency per se caused the effect, and not the corrosion.

A part of the answer can be found in [36, 37]: In [37] for example, the effect of test frequency on crack propagation was greater in dry air than in saturated wet air for 2024-T3, at least at low ΔK. The frequency effect, however was small anyway, i.e. the crack propagation rate at 0,4 Hz was only about twice as high as at 57 Hz. The corrosion effect was somewhat more pronounced, i.e. a factor of about 3 between dry air and saturated wet air.

A different answer can be found in [39]: In air, there was no frequency effect, but in a 3% NaCl solution the crack growth rate at 0,1 Hz was about 2,5 times higher than at 10 Hz, where it was very similar to that in air. The material was an SAE 4340 Steel with a yield strength of 1241 MPA. At the lower yield strength of 896 MPA the environmental influence on the crack growth rate of this steel was very small, being less than a factor of two even at 0,1 Hz, so there cannot have been any noticeable frequency effect.

Conversely, a large influence of test frequency on corrosion fatigue crack growth rate of five different steels was stated in [41], being about a factor of 10, if the frequency was lowered from 10 Hz to 0,01 Hz.

In [40], a considerable influence of corrosion on the fatigue life of three AlMg alloys was shown even at 10^5 cycles to failure [reduction from 200 MPA to 160 MPA], but the effect of test frequency was almost negligible between 17 and 190 Hz. Incidentally, 10^5 cycles take about 9 minutes and there was the above-mentioned large environmental effect! Several additional papers [36, 37, 42-48] concern the effect of testing frequency, but will not be discussed here.

Regarding corrosion fatigue tests at low frequency, there is a further aspect: Time and money are always short; also, there are many other fatigue parameters to be accounted for, for example scatter of fatigue life, which requires many test results. It is therefore more useful to carry out many tests at higher frequencies, than just one at a low, servicelife frequency, and to account for the frequency effect by a factor on fatigue life.

For crack propagation tests, there is a "trick", long known to offshore test engineers, to cut down on testing time: Determine the Paris curve only in segments at the low frequency considered neccessary and bridge the gaps between these segments by extra - and interpolation, employing the C and n values of the Paris equation, as found from the crack propagation test in the corrosive medium. However, the time in the environment will then obviously be shortened.

Testing frequency per se after all is not a measure of test duration or time in the environment, because it is obviously possible to increase the stress amplitude (or ΔK range) and thus lower the number of cycles to failure and the test time. This "trick" has the disadvantage of increasing the local strain amplitudes, which may be incorrect even for unnotched and notched corrosion fatigue tests and certainly is incorrect for rivetted joints, because it may loosen the rivets, or crack the corrosion protection, thus allowing the entrance of the medium into the unprotected rivet hole.

From the above results the following conclusions can be drawn:

- The effect of test frequency on fatigue life or crack growth rate ranges from nil to a factor of about ten. The effect is small, when the complete life to failure consists of a long crack initiation and

a short crack propagation phase; it is thus larger for crack propagation than for crack initiation.
- A corrosive environment can already be detrimental to fatigue life after a few minutes, contrary to general corrosion, which takes a much longer time to have an effect. In such cases, pitting cannot have been the cause.

EFFECT OF FATIGUE PARAMETES ON CORROSION FATIGUE

Mean Stress. In fatigue tests in air, tensile mean stresses have a detrimental effect on fatigue life or -strength. In general, this effect is the larger, the higher the tensile strength of the material is, the so-called "mean stress sensitivity" [49].

Only a small number of corrosion fatigue tests have been carried out at different mean stresses. Fig. 7 [19] shows that the effect of tensile mean stresses (at R = 0,1 and 0,5) was much larger in Severn River water than in air, especially at 10^8 cycles. However, this is so only for the number of cycles to failure: crack growth was hardly affected by an increase of tensile mean stresses, see Fig. 8. There was (the usual) slight effect of the corrosive medium on crack growth, but not an additional effect of tensile mean stress. Figs. 7 and 8 are from the same test programme on the "marine", i.e. corrosion resistant Al-alloy 5456-H 117 [19].

Other effects are also visible in Fig. 7: This material certainly is not "corrosion fatigue resistant". The fatigue strength at 10^8 cycles and at R = 0,33 in Severn river water is less than one fifth than that in air; even at R = - 1 this value decreases to about one third. The data of Fig. 7 are for the unnotched state.

The similar material AlMg 4,5 Mn was tested in the form of two different welded joints [22], see Fig. 9: Again, a very large effect of the mean stress was found in seawater for both types of joint. There was only a smaller mean stress sensitivity in air at 10^5 cycles and a very large effect of the seawater per se.

Constant Amplitudes Vs. Variable Amplitudes. It has been known for many years that constant amplitude tests will usually give different results than variable amplitude tests, even in a qualitative sense ("rating" of materials for example) [50]. According to some test programmes, this is even more so if the fatigue tests are carried out in a corrosive environment:

Some results of the RAE contribution [7] to the FACT programme [11] are shown in Fig. 10: The material 7010 was tested in two different heat treatments, T-7651 and T-7451. Under constant amplitudes, the crack propagation rate was similar in air; salt spray was more detrimental for the T 7451 conditions (about a factor of three) than for the T 7651 condition (about a factor of 1,5). Under the Falstaff sequence however, there was

- no significant effect of the environment and
- practically no difference between the two heattreatments.

In this RAE contribution, normal fatigue tests with notched specimens (K_t = 2,5) have also been performed, see Fig. 11: At 10^7 (= 110 hours test duration) constant amplitude cycles there was a large effect of corrosion , the fatigue strengths decreasing up to 33 percent of that in air. Both heattreatments were slightly different at 10^7 cycles in air, but equal in salt spray.

Under the Falstaff sequence, however, there was no effect of corrosion and no difference between the two heattreatments in air or in salt spray. What is more, and also contrary to the c.a. behaviour, this was true for 4000 flights (= $3{,}2 \cdot 10^5$ cycles, about 6 hours test duration) as well as for 55000 flights (= $4{,}4 \cdot 10^6$ cycles, about 80 hours test duration).

A similar result was obtained by the author in [51]: Two amagnetic steels, one of them a stainless one, were tested under constant and variable amplitudes in air and sea water. Although the variable amplitude tests lasted much longer, the damaging effect of corrosion was much smaller than for the constant amplitude tests. This was true for both steels and for three different specimens, two of them welded. The details of this test programme were presented by the author at the 1979 ICAF Symposium in Brussels [52].

The results from the FACT - [11] and the CFCTP - [12] programme of AGARD with a 1½ dogbone rivetted joint also showed a difference between c.a. and v.a. tests in a corrosive environment, compare Figs. 12 and 13: The IABG tests with the Falstaff sequence furnished a smaller reduction due to corrosion, especially at the lower maximum stress of 238 MPA. Preexposure had no detrimental effect on the number of flights to failure in air at this maximum stress, while it reduced the number of cycles to failure at constant amplitudes to about 80%. However, the corrosion protection scheme (and the material) for the German specimens were different.

Another effect can also be seen from Figs. 12 and 13: The effect of corrosion on fatigue life was more pronounced at the higher stress levels for both c.a. and v.a. tests, although the time in the environment was shorter by a factor of almost ten for the c.a. tests and of about three for the Falstaff tests. The reason may have been the increased loosening of the rivets in their holes by the higher maximum stresses. Before the fatigue tests, the corrosion protection system had been cracked in every specimen by a high load at - 50° C.

Fig. 14 shows the results of the NLR contribution to the FACT programms [11]: Contrary to all other participants, the NLR used c.a. tests, the Falstaff sequence and the Minitwist sequence with the 1½ dogbone specimen, albeit with different materials. Still, it is the only programme known to the author where these two different stress-time histories were used. Only a small part of the results is shown in Fig. 14: For the 2024-T3 with the F-28 corrosion protection system the maximum reduction due to corrosion was a factor of 2,4 under constant amplitude and of 1,9 under Minitwist loading. For 7075-T6 with the NF5 protection system, the maximum reduction was a factor of 2,6 for constant amplitudes and of 1,7 for Falstaff loading. Qualitatively at least, these results agree with those of the author mentioned above, i.e. the corrosive damage was less for realistic stress time histories than for c.a. tests.

To calculate this effect correctly by damage accumulation hypotheses (local approach, Miner, Paris, Elber) would probably be difficult; in crack closure models one would have to assume that crack closure was different in air and in the corrosive environment. This has been noticed in some research works, but for actual calculations the numerical values of crack closure (ΔK_{eff}) would have to be determined experimentally for each individual case.

<u>The Effect Of Geometrical Notches, Welds, Pits and Cracks on Corrosion Fatigue.</u> As mentioned previously, in many metallic materials there is a large effect of the corrosive environment on fatigue- life or -strength if the test specimen is unnotched. Reductions of the fatigue strength at high numbers of cycles to failure range up to a factor of 8 and higher, especially for high

strength steels [47], but also for Aluminium alloys [19], especially at high mean stresses. This is also true for so-called corrosion-resistant steels [53] and "marine" aluminium alloys. Since the fatigue notch factor K_f never reaches so high a number [54], it can be said that corrosion fatigue is be more detrimental than even the sharpest notch possible.

However, real components always have notches; therefore the behaviour of notched specimens under corrosion fatigue conditions is more important and it is seen that the effect of notches and of corrosion are not additive. On the contrary, some materials show no corrosion damage in the notched condition, only in the unnotched one, for example Ti-6Al-4V. According to [55], see Fig. 15, as soon as even a mild notch was present, there was no additional reduction in fatigue strength due to corrosion (3% NaCl at 80° C). In other materials, a notch at least reduces the additional effect of corrosion found in the unnotched state.

Corrosion pits have been modeled as if they were stress concentration factors and the fatigue life or fatigue life reduction has been thus calculated. Figs. 16 and 17, due to Prof. Schijve, show such a pit and the corresponding model (Fig. 18), which after Peterson had a $K_t \approx 6,0$. Other authors [34] have treated the pit as a crack, the remaining life being calculated according to crack growth formulae. The actual effect of service or artificially - developed corrosion pits on fatigue strength has been investigated by several authors: Fig. 18 [14] shows the dependence of fatigue life of 2024-T3 on pit depth.

Schijve in [56] found a "disastrous" effect of pits as small as 0,33 mm deep, the fatigue strength being reduced by a factor of more than 2,5 for 7075-T6. However, both authors [14, 56] compare the fatigue strength with pits to that without pits, i.e. in the unnotched condition, which may overstate this effect.

Fatigue tests were carried out at IABG [57] on unnotched specimens cut from a 2024-T3 sheet corroded in aircraft service. No effect was found by comparison with new, uncorroded specimens.

Corrosion pits can be very detrimental to the fatigue life of high-strength steels, as shown in Fig. 20 for the case of automobile coil springs, which are made of a steel similar to SAE 4340 with a tensile strength of about 1800 MPA [23, 46]. After deliberate damage to the corrosion-protection system by the IABG "gravel-damage-machine", individual coils were precorroded by 5 weeks of cyclic corrosion ("VDA-Wechseltest") which automobile manufacturers use in Europe. A reduction to about 60% of the fatigue strength in air was found and the fatigue failures always started from corrosion pits. Before the corrosion protection was applied, the springs were shot peened. Without this treatment, the corrosion effect on fatigue strength would presumably have been even more detrimental. Other papers on the effect of pits see [58, 59, 60].

As mentioned before, corrosion also can be very detrimental to fatigue life without any pits being present, be it because of the short testing time or if the material does not pit. An example is shown in Fig. 21 [61], based on constant amplitude torsion tests of 6061-T6 aluminium drive shafts: Precorrosion of 1500 hours in salt spray at a static preload did affect fatigue life in air only at numbers of cycles to failure $N > 10^6$. If there was no precorrosion, but the fatigue test was carried out in a 3,5% NaCl "shower", the effect was similar, i.e. only after about 10^6 cycles corrosion damage appeared. If the fatigue test after the precorrosion was carried out in the 3,5% NaCl "shower", a damaging corrosive effect was already found after about 10^3 cycles, corresponding to 30 minutes in the "shower". No pits were present after any of the tests, some of which lasted for 1500 hours in saltspray plus 150 hours of fatigue test in the saltwater "shower" ($1 \cdot 10^7$ cycles).

Welds behave similar to notches, i.e. the corrosion effect usually is smaller than with unnotched specimens. This can be inferred from a comparion of [19] and [22] where the very similar "corrosion-resistant" aluminium alloys 5456 and AlMg 4,5 Mn were used: A "disastrous" corrosion effect on the unnotched specimens of [19], see Fig. 7, a smaller effect on the welded specimens of [22].

On crack propagation under corrosion fatigue conditions, there is a large body of results, some of them in handbooks [62 - 65], many more in individual papers [4, 6 - 8, 13, 17, 18, 26, 37 - 39, 42 - 44, 66 - 75].

The general results of these corrosion fatigue crack growth tests is that corrosion is less deleterious than for fatigue tests on notched specimens and much less deleterious than fatigue tests of the unnotched material. This can be seen, for example by comparing the results of [21] and [22]: A very large corrosive influence on the fatigue strength of welded joints of AlMgSi1 (=6061-T6) no influence at all on crack growth, see Fig. 22. Usually, either fatigue (crack initiation) or crack propagation tests are performed, direct comparions are therefore rarely possible. One exemption is [7], compare Figs. 10 and 11: Crack propagation rate is not much affected by the salt spray (at constant amplitudes) but the fatigue strengths at 10^7 cycles are lowered to less than half for the notched specimens with a $K_t \approx 2{,}5$. (For "Falstaff" tests however, neither the fatigue lives nor the crack growth lives were affected by the corrosive medium as mentioned before).

There is one glaring exception to the above rule: Ti-6Al-4V alloy is somewhat sensitive to corrosion in the unnotched conditions, see Fig. 15 [55], unsensitive in the notched condition [55], but extremely sensitive if a crack is present.

The best example of this is due to Wanhill et al [6], and shown in Fig. 23, where 2024-T3, 7075-T6 and Ti6Al4V are compared for crack initiation and crack propagation lives. The "Twist" stress time history was used and the stress levels were applied according to the specific weights of these materials, i.e. 70 N/mm^2 for the Al-alloys and 113 N/mm^2 for the Ti-alloy. In air and in 3,5% NaCl the Ti-alloy was far superior, in fact the notched specimens with a central hole ($K_t = 2{,}66$) did not initiate a crack in air nor in NaCl after 60000 flights, while 2024-T3 showed a reduction from 11000 to 4500 flights and the 7075-T6 specimen initiated cracks after 7000 flights in air and 4500 in NaCl.

A 1 mm crack starter was then cut with a jeweler's saw and the results changed dramatically: The titanium specimens failed after 15000 flights in air and after 1000 flights in NaCl. For the Al-alloys, however, corrosion reduced the crack propagation life only from 12000 to 6000 flights (2024-T3) and from 2700 to 400 flights (7075-T6). Thus, the crack propagation life of the Ti-alloy in air was similar to that of 2024, but in the corrosive environment it was only about one sixth of that of 2024.

The conclusion is that Ti-6-4 is superior only as long as there are no cracks or a perfect corrosion protection scheme can be maintained for all the life even in the cracked condition. (The damage tolerance requirements assume crack-life defects to be present from the start!).

The largest collection of papers on Ti 6-4, it's corrosion insensitivity in the notched condition and it's extreme sensitivity in the cracked condition can be found in Wanhill's comprehensive review [13]. For example, he quotes crack propagation tests with the B-1 wing pivot spectrum [83]: Humid air (> 90% R.H.) resulted in a much faster crack propagation than dry air, see Fig. 24. Especially disturbing is the much faster crack propagation in humid air of specimens with an interference fit fastener (lower half of Fig. 25), because this is contrary to results with such specimens of other materials.

Other papers on crack propagation of Ti-alloys, albeit at constant amplitudes, also show the extremely damaging influence of a corrosive environment [13, 16, 44, 62 - 65].

The conclusions from this section are:

- In a corrosive environment, tensile mean stresses have a much larger (damaging) influence on fatigue strength than in air. This is valid for the unnotched, notched and welded conditions and even for materials not "mean stress sensitive" in air as well as for "corrosion resistant" materials.
- For corrosion fatigue crack growth the influence of tensile mean stresses is no different from that in air.
- Constant amplitudes are more detrimental to corrosion fatigue strength than variable amplitudes. This is also valid at high numbers of c.a. cycles, and even when the v.a. test takes longer than the c.a. test.
- Some materials do not show a deleterious influence under v.a. loading at all, but a considerable influence under c.a. loading.
- Even for rivetted components (with corrosion protection) there can be a slightly larger effect of corrosion under c.a. loading.
- In the unnotched condition, all structural materials show a deleterious effect of corrosion on fatigue strength, ranging from disastrous to significant.
- In the notched and welded condition, this influence is generally smaller. Ti-6-Al-4V is not impaired at all.
- Corrosion pits can considerably reduce the fatigue strength. However, the absence of pits does not mean corrosion will not have decreased fatigue strength. Some materials will not pit even

at very long precorrosion and corrosion fatigue test durations, but they do show a deleterious influence of corrosion on fatigue strength.

- The influence of a corrosive environment on crack growth at constant amplitudes is even smaller than that on fatigue strength of notched specimens. There are materials whose crack propagation properties are not at all impaired. This is especially valid for variable amplitude loading. Thus a corrosion fatigue crack propagation test under v.a. loading will generally result in the least deleterious effect; it may even by nil.
- However, Ti6-4 is the exception to this rule: While not impaired by corrosion in the notched condition, it is extemely sensitive in the crack propagation phase. Cracks in Titanium components must be avoided, if corrosion is to be expected in service, or a perfect c.p. scheme must be maintained even in the cracked state.

EFFECT OF CORROSION PARAMETERS ON CORROSION FATIGUE

The Corrosive Medium

Most corrosion fatigue tests have been carried out in artificial seawater according to ASTM [75] or in the somewhat simpler 3,5% NaCl solution. Very rarely, real sea water has been used, which usually showed a slightly more damaging effect [76, 77, 78]. In a few test programmes, the NaCl content was increased up to 15%, trading the (hoped-for) more severe corrosive effects for the (assumed) too-short testing time in the environment. This was usually not successful [40,45], there was a moderate decrease of fatigue life with increasing the NaCl content, followed by an increase of fatigue life with further increase of NaCl content. With a similar intention, a higher medium temperature was sometimes used [55].

For aircraft and automobile corrosion fatigue tests, 3,5% to 5% salt spray is usually used; also seemingly less aggressive environments like tap water, distilled water, moist air, a "saline atmosphere", bilge fluid, sump tank water, jet fuel etc. have been applied as fluids, sprays or fogs.

To the author's knowledge, few test programmes have attempted to simulate the changing environmental conditions of aircraft service, for example by alternate immersion tests [79].

The automobile industry, however has been using "cyclic" corrosion tests for decades, however mostly for determining the protective quality of coatings or paints, i.e. for corrosion - and not corrosion fatigue tests.

Because the results are contradictory and few test programmes with different corrosive environments can be directly compared, the results are contradictory:

Jarfall, for example, in two papers [79,80] obtained the following: By alternate immersion in distilled water or by alternate humid and dry air the FACT 1½ dogbone rivetted - joints were just as damaged as by salt spray [79]. This is not too surprising, since the joints were corrosion protected and the effect of even the salt spray environments was small. However, in [80], unnotched and unprotected specimens of 7075-T6 (!) were tested, if only in humid air with condensation or in alternate immersion in tap water and even then the corrosive effect was small and equal for both media, i.e. the fatigue life decreased only from $\approx 5 \cdot 10^5$ c.a. cycles in air to $2{,}5 \cdot 10^5$ in alternate immersion. What is more, a precorrosion of 6 months did not have any effect!

On the other hand, a "saline atmosphere" in [22] was just at damaging as seawater to the fatigue strength of butt-welded and fillet - welded joints of AlMg 2,5, a "corrosion resistant" alloy.

The effect of sump tank water on crack growth of Ti-6Al-4V was compared to that of high humidity air and 3,5% NaCl in [81]: As determined by others and mentioned before, 3,5% NaCl was catastrophic, but sump tank water also was very detrimental (about a factor of 10 in the crack growth rate). It was catastrophic, if hold times under maximum load were applied.

In [82], crack growth arrest in sump tank water was reported for 2219-T852, 7475-T7351, 7050-T7351, 2024-T3 and 7475-T761. The ΔK_{th} values for the latter two materials were extremely high in sump tank water, (by a factor of up to 2,0 compared to the air values. Even in saltwater, ΔK_{th} was higher for 7475-T761. This was ascribed to a much lower ΔK_{eff} in sump tank water as a result of crack closure, roughening etc.

On the other hand sump tank water did slightly increase crack growth for 2024-T3.

The real corrosive environment of aircraft in service is not well known; hopefully the paper by Swartz, Miller and Hoeppner [96] at this Symposium will improve this situation. In this respect, an observation by Wanhill [97] is helpful: After a few hours of fatigue testing in saltspray, the striations typical for fatigue have corroded away. In tap water, this is not the case. However, components of aircraft which have seen a corrosive environment for years, still show striations. The conclusion is that salt spray or salt water cannot have been acting in service. However, in view of the Swedish results mentioned above [79, 80] and others this does not necessarily mean that the service environment is more benign to fatigue life than the salt spray typically used in laboratory tests.

In any case, the corrosive medium employed in such tests should be described more completely than by the usual "3,5% NaCl"; it's pH value and temperature should be controlled and described in the test report.

Precorrosion

In order to save the time and costs of corrosion fatigue tests, specimens and components are often precorroded in a nomal (i.e. outdors) or artificial atmosphere, the later usually being saltspray or - fog. In a few test programmes, "service precorrosion" was employed by cutting specimens from used aircraft.

In [85, 86], for example, specimens were prepared from the upper wing carry - through surface of a B-707; the material was 7178-T6; this wing plank had been replaced because of severe exfoliation corrosion after more than 10 years of service. The rivets were removed and the original corroded holes used as open hole notches. Other, nominally unnotched, but severely corroded specimens were machined from this wing plank between the rivet holes. For comparison, uncorroded unnotched and notched specimens were made by machining away the corrosion. The results are seen in Fig. 25: A very large influence of this natural precorrosion on the unnotched specimens, a somewhat smaller one on the notched specimens (both tested in air). In this large test programme we then attempted to simulate this behaviour by precorroding similar notched specimens, albeit of 2024-T-351 and fatigue testing them in saltspray, but unsuccessfully, see Fig. 26: Precorrosion of 500 hours, followed by testing in air showed no effect up to about $5 \cdot 10^5$ cycles, followed by a sudden drop of the SN-curve. Precorrosion and fatigue testing in saltspray resulted in considerable reductions.

Incidentally, the frequency effect was quite small, being less than a factor of two in life between 0,2 Hz and 120 Hz. Corrosion fatigue testing at 0,2 Hz showed a small deleterious influence of the precorrosion, see Fig. 25.

Rivetted double-lap joints of 2024-T351 with a corrosion protection scheme, antifay between the sheets, but dry assembly of the rivets, were also investigated, see Fig. 27: The effect of even the most severe combination (500 hours precorrosion plus fatigue in saltspray) was small at low stress amplitudes, becoming larger at high stress amplitudes. Again the frequency effect was negligible, compare the tests at S_a = 50 MPA, and the precorrosion did not have a significant effect.

Other fatigue tests with naturally or artificially precorroded specimens and components see [11, 14, 58, 88-92]. In the IABG contribution [20] to the FACT [11] programe, precorrosion times were increased 5 - fold from 72 hours to 360 hours. Although the corrosion attack on the protective paint system was visibly more severe, especially around the rivet heads, no effect on the number of flights to failure was noted.

The general conclusions from these programmes are

- Precorrosion can be very detrimental on fatigue life or strength in unnotched and notched specimens.
- It is less detrimental for rivetted joints, as long as the corrosion protection system is not breached and as long as the rivets remain tight in their holes.
- It is difficult to simulate the "natural" precorrosion occurring in service by artificial precorrosion in the laboratory.
- Prolonging the precorrosion time in the laboratory will usually increase the apparent corrosion attack but will not neccessarily decrease the fatigue life further, especially in rivetted joints.

Cathodic-Protection

All metals can be cathodically protected by more anodic paints, coatings and metals. This will usually restore their fatigue life to that in air, as long as the protective capacity is not used up. In chromate-containing primer this capacity is prolonged by the slow "leaching" of chromate.

Some authors have claimed that cathodic protection will increase crack growth in steels because of hydrogen embrittlement (several papers in [75] and [93]), while increasing crack initiation life. If this were true, the cathodic protection of oil rigs should be taken off as soon as cracks would appear, neglecting for a moment the difficult problem of finding these cracks and the further problem that the crack initiation life in uncracked locations would then decrease! If this claim were true for Al-alloys, cathodic protection should not be used at all in aircraft since the damage tolerance concept assumes crack-like defects to be present from manufacture onwards!

Anyway, the corrosion fatigue life of the 6061-T6 drive shafts [61] mentioned before (Fig. 21) was improved beyond that in air by a zinc-containing paint and in [18] crack propagation in seawater was slowed down in the alloys 5086-H110, 5086-H117, 5456-H116 and 5456-H117 by the optimum cathodic potential of about - 1,4V, especially at low ΔK values. The ΔK_{th} values were considerably increased from about 8 MPA$\sqrt{m}$ to 10 to 20 MPA$\sqrt{m}$. In one test, a crack was grown under freely corroding conditions. At some point, the specimen was polarized cathodically and the crack then stopped completely.

Speidel in [94] investigated the effect of cathodic protection on fatigue crack growth in 7079-T651 and Ti-6Al-4V alloys. For the Al- and the Ti-alloy it was possible to alleviate the damaging effect of chloride, bromide and iodide additions to water on crack growth rate; however, no tests in air were carried out, so it is not possible to conclude that the corrosive effect of the aqueous solution could be neutralized.

Crevice Corrosion

Corrosive liquids trapped in crevices tend to become more aggressive with time. This so-called "crevice corrosion" has been known for a long time. However, crevice corrosion fatigue, i.e. the effect of this more aggressive medium on fatigue-life or-strength has not been investigated to the author's knowledge, with the exception of one report of himself and Lachmann [95], albeit on steels for steam turbine shafts and blades: Due to crevice corrosion, there was a relatively small reduction of the crack initiation life of unnotched LCF-type specimens, compared to the life in deaerated water, but without a crevice.

Cracks, especially when they remain stationary and open for a long time, as in aircraft on the ground or in level flight in good weather, should be ideal places for crevice corrosion to occur. Also the faying surfaces of typical aircraft joints, the gaps between rivetshaft and -hole could be prone to crevice corrosion. It would probably be a good idea to deliberately investigate crevice corrosion fatigue, requiring however low test frequencies with long hold times under load and appropriate specimen designs. At the usual high test frequencies the medium will probably be "pumped" out of and fresh medium sucked into the crack by the opening and closing of the crack and no crevice corrosion conditions will then occur.

Corrosion Protection Systems

If components were used in corrosion fatigue tests, they usually had realistic corrosion protection systems as used in certain aircraft types*. In a few cases, these systems were deliberately damaged, for example by leaving the fastener heads free [98], or left off completely [99] to simulate "worst-case" conditions. In the FACT-[11] and CFCTP-[12] programmes, for example, the paint around the fastener heads was deliberately cracked by a few high loads at -50° C to simulate realistically the service conditions of tactical aircraft.

Most of the test programmes with components were already mentioned in connection with other subjects [5, 7, 14, 20, 23, 25,

* To use such systems for unnotched [100] or notched specimens will not give realistic results anyway.

46, 79, 80, 86, 89-91], others are referenced in [100-104]. The general result from most of these test programmes is that the corrosion protection systems decrease and sometimes negate the corrosion damage, i.e. with a good system the fatigue life in air can be obtained.

Two examples of such a case [98] are shown in Figs. 28 and 29. The single-lap rivetted joint of 8090-C Al-Li alloy lasted as long in saltspray as in air, see Fig. 28 even if the Titanium Hi-Lok bolts had no protection system and the fastener heads were left free. The test frequency in saltspray was 0,2 Hz, so the fatigue test duration was about 100 hours, and these rivetted joints had been precorroded for 500 hours in 5% NaCl spray concurrently with 80 cycles/day of $S_a = \pm$ 70MPA.

Similar joints of 2024-T351 were also tested, see Fig. 29, and again, no effect of corrosion was observed despite the different precorrosion treatments or the ph 3,0 salt spray and despite the fact that the Titanium fastener heads in four test series were unprotected.

It can only be concluded from these results that the bolts had closed off the corrosive environment from the bolt holes.

In the FACT and CFCTP programmes [11, 12] often mentioned before, relatively small reductions of corrosion fatigue life under constant amplitude loading and still smaller reductions under Falstaff and Minitwist loading were noted for the 1½ dogbone rivetted joint, see for example Figs. 12, 13 and 14, ranging from about 1,6 to 2,6. The rivetted joints had typical aircraft corrosion protection systems, among them NF-5, F-28, MRCA, US Navy, F-16, etc. All of them had been deliberatly damaged before the fatigue tests by a few high loads at -50° C.

Livet in [102] as early as 1969 investigated two corrosion protected rivetted joints. They differed only in the protection processes and had a cut center flange to "simulate the effect of a crack in a wing skin on the fatigue behaviour of a stringer". The environment consisted of 1000 hours saltspray before fatigue testing and 600 hours saltspray after 7000 fatigue cycles. The results of this very useful programme are shown in Fig. 30: Irrespective of the type of corrosion protection, the fatigue life was influenced only to a small degree by corrosion. These results would have been even more interesting, if a corrosive environment during the cyclic loads had been applied!

A US-Australian cooperative programme was presented in [5]. It differs from all other tests in that the bolted joints were of steel D6AC, which supposedly is very sensitive to corrosion because of it's high static strength. The specimen was a single lap shear joint with H-11 Taperloc fasteners. The contaminants distilled water and hydrochloric acid in the Taperloc holes were not deleterious under constant amplitude loading but under spectrum loading the latter contaminant resulted in a "drastically shortened fatigue life".

A 5% salt spray "shower" decreased the constant amplitude fatigue life of the B-window post of the Audi A-8 to one fifth [99], although the material was a 6000-series alloy. The jointing process was "punch-rivetting", a new process developed especially for the aluminium body of this car. To simulate worst case conditions the normal corrosion protection was left off.

Many other test series showed the beneficial effect of shot peening on corrosion fatigue strength of steels and Al-alloys, even without further corrosion protection. Considering that tensile mean stresses are especially deleterious to corrosion fatigue strength, one explanation for this beneficial effect could be that the compressive mean (residual) stresses set up by shot peening lower the damaging effect of corrosion, as much as tensile mean stresses increase it.

The conclusions from this section are:

- The damaging effect of a corrosive environment can be almost completely prevented by a tight fit of rivets or bolts in their holes and a good corrosion protection system;
- this tight fit and good corrosion protection must however be maintained for all the fatigue life.

CORROSION FATIGUE LIFE REDUCTION FACTORS

Until such time as results from full scale corrosion fatigue tests are available, the following reduction factors, to be placed on the fullscale fatigue test life, may be helpful: Chrichlow in [105] differentiated between three environments (internal structure, unexposed; external structure, exposed; and "active" environment, meaning "fuel, sump water, food and human waste products and others more active than normal sea coast atmosphere"). The first environment was to be accounted for by a factor of 1,25, the second of 2,0 and the third of 4,0, all valid for Al-Ti- and steel alloys.

These factors however were not be applied to the result of a full scale test, but to the results of development tests on components and for fatigue life calculations.

Gruff and Hutcheson in 1969 [14] suggested a "mean scatter factor", meaning a life reduction factor "required on tests of new wing structures when hole corrosion protection is considered questionable" of 2,5 or less, depending on years of operation of the aircraft and other parameters.

Based on some component tests discussed above [10, 11, 86-92] a factor of two would probably be sufficient.

RULES FOR CORROSION FATIGUE TESTS IN THE LABORATORY

All the test results and the conclusions discussed up to now are based on corrosion fatigue tests in the laboratory.

However, as mentioned in the introduction, it is not possible to simulate correctly the corrosion parameters of service in a laboratory test. So the question always remains: "Can the results we have obtained by laboratory tests be used for assessing the influence of corrosion on fatigue life in service, i.e. for assessing the durability?"

We can at least try by carrying out laboratory tests in the following way:

- Test actual components with their corrosion protection system.
- Damage the corrosion protection system to simulate cracking due to local high strains at notches (rivet holes) and due to accidental damage.
- Use the applicable stress-time history, i.e. constant amplitudes for the fuselage, variable amplitudes (Falstaff, Twist etc.) for the wings.

- Do not overload compared to the service loads, especially if the component is a rivetted joint. This means long and expensive tests.
- Use the correct corrosion medium (what is the correct corrosion medium for the interior and exterior surfaces of fuselages or wings?).
- Apply the corrosion medium all the time, even when the fatigue machine is not running, to increase corrosion times; if possible, apply static loads during this period, to open cracks to induce crevice corrosion conditions.
- Develop a "corrosion fatigue crack propagation specimen" in order to assess the corrosion effect on crack propagation better than with the usual sheet specimens in salt water fog. At least have the real corrosion protection system on the specimen to see if the leaching of the cromate has an influence.

SUGGESTIONS FOR FURTHER WORK

In the opinion of the author, a large number of the problems discussed above can be solved by in future carrying out the full scale fatigue test under corrosion. There are a lot of good arguments for such a test:

- The real structure is tested, with the real corrosion protection system. (This would require that the full scale test article be completely painted, which has not been the case up to now).
- The service loads are simulated best, because the individual stress-time history of the aircraft type is applied, not a standard one like Twist (nor constant amplitudes). Also the structure is not overloaded (10% at best, as by Fokker and Airbus), compared to components, which usually are tested at higher stress levels than service to reduce cost.
- A full scale fatigue test is the longest-running test known (1½ years to 15 years, the latter for some military aircraft). The argument that two or three years are still shorter than service life is not valid, because all other corrosion fatigue tests have a much shorter duration and we have to base our conclusions on tests to be able to assess and predict durability before some unexpected failures occur in service .
- A direct comparison between uncorroded and corroded fatigue life is possible, by, for example fitting the corrosion chamber to one side of the fuselage, leaving the other side free, or to a part of one wing.

- Deliberate damage to the corrosion protection system can be introduced, based on experience with previous aircraft.
- Repair schemes for the corrosion protection system can be tested as well.
- The corrosion resistance (as apart from the corrosion fatigue resistance) is tested as well.
- Damage tolerance in the corroded condition is tested as well.
- Scatter of corrosion fatigue life is tested as well, if several to many similar structural details (for example windows) are included in the corrosion chamber.
- The additional cost of corrosion in such a test is low, considering the huge cost of a conventional full scale fatigue test of up to $ 50 million for the test and not much less for the structure, which is destroyed by the test. IABG assumes that 1-3 per cent of these costs would be sufficient.

The fatigue tests with aged aircraft that some manufacturers have been performing for years are not equivalent to the test suggested above, because they are "after the fact" - tests, i.e. they occur decades after the introductin of a new aircraft type. They nevertheless would be very useful if they were carried out on aircraft which were not just old in flying hours or landings, but in addition badly corroded.

A better compromise, at least for the fuselage, would be to perform the so-called "barrel" tests (Airbus, Fokker) as a corrosion fatigue test by fixing a corrosion chamber to a part of the barrel. The additional cost would be very small.

The problem of the correct corrosion medium, which may also be different for the inside and outside of the fuselage, still remains.

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Fatigue Parameters

stress amplitude
mean stress
stress-time history
crack initiation
crack propagation
K_t
K_f

stress type (i. e. bending, axial, multiaxial)

specimen or component size

material (Steel, Al, Ti)

etc, etc

Corrosion Parameters

material
type of medium (pH, natural, artificial)
medium temperature

time in the environment
stress (Magnitude of Stress)

corrosion type
(pitting, exfoliation)

specimen or component thickness

corrosion protection (active, passive)

etc, etc

corrosion fatigue parameters ?

Fig. 1: Fatigue and Corrosion Parameters

	Laboratory Test (Specimen)	Service (Component)
Test Frequency	high	low
Time in the Environment	short	long
Corroding agent	3,5 % Na Cl (water or spray)	?
Corrosion attack	all the time	Part of the time
Stress Amplitudes	Constant amplitudes	Variable amplitudes
Holdtime in the environment without or with constant stress	none	very long (military aircraft)
Test article shape	unnotched, cracked (?)	notched, rivetted, cracked
Corrosion protection	no	yes
Pitting possible	no (not in a short time)	yes
Crevice corrosion possible	no	yes
Cathodic corrosion possible	no	yes

Fig. 2: Differences between Laboratory Corrosion Fatigue Tests and Service

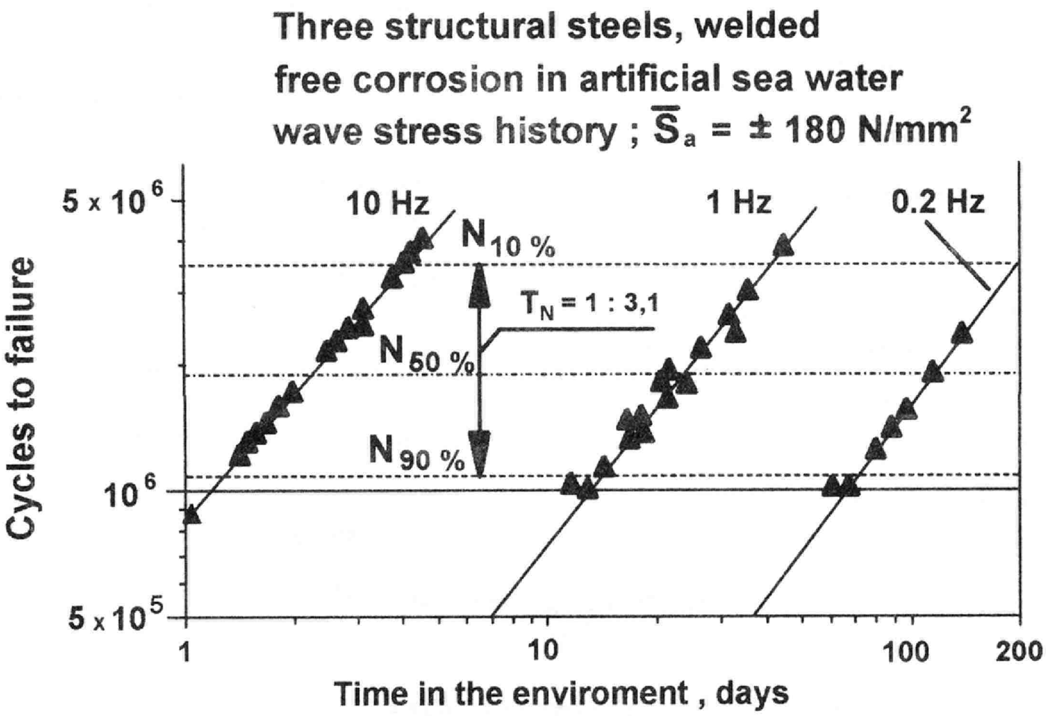

Fig. 3: Influence of Test Frequency on Fatigue Life [27]

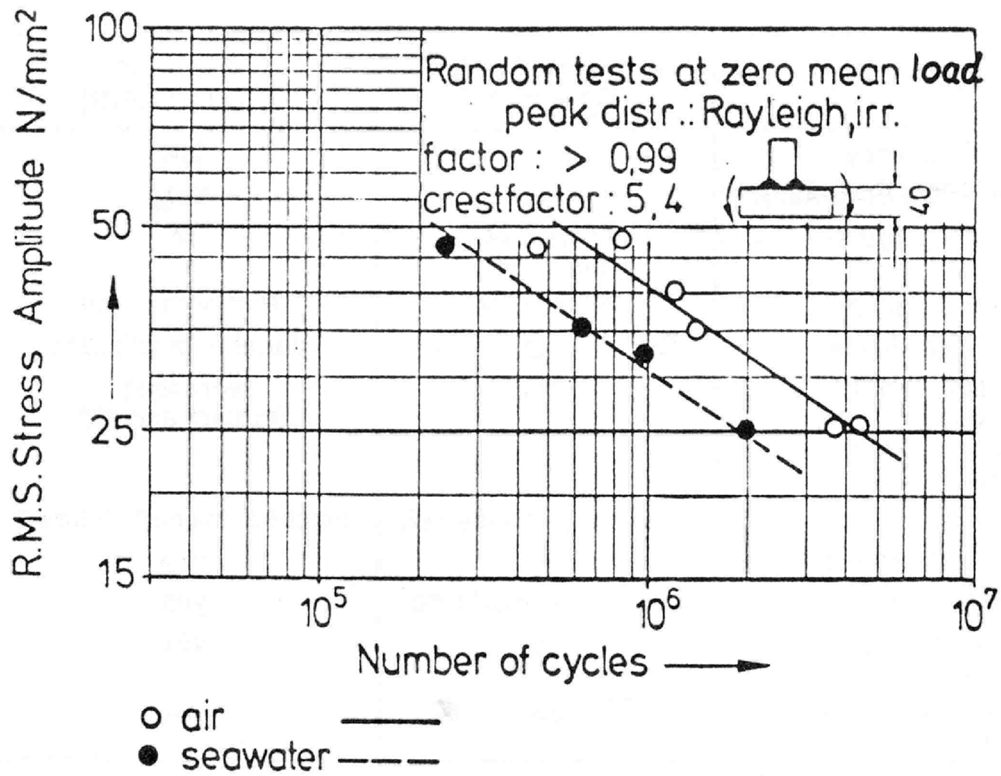

Fig. 4: Influence of Test Frequency on Fatigue Life [75]

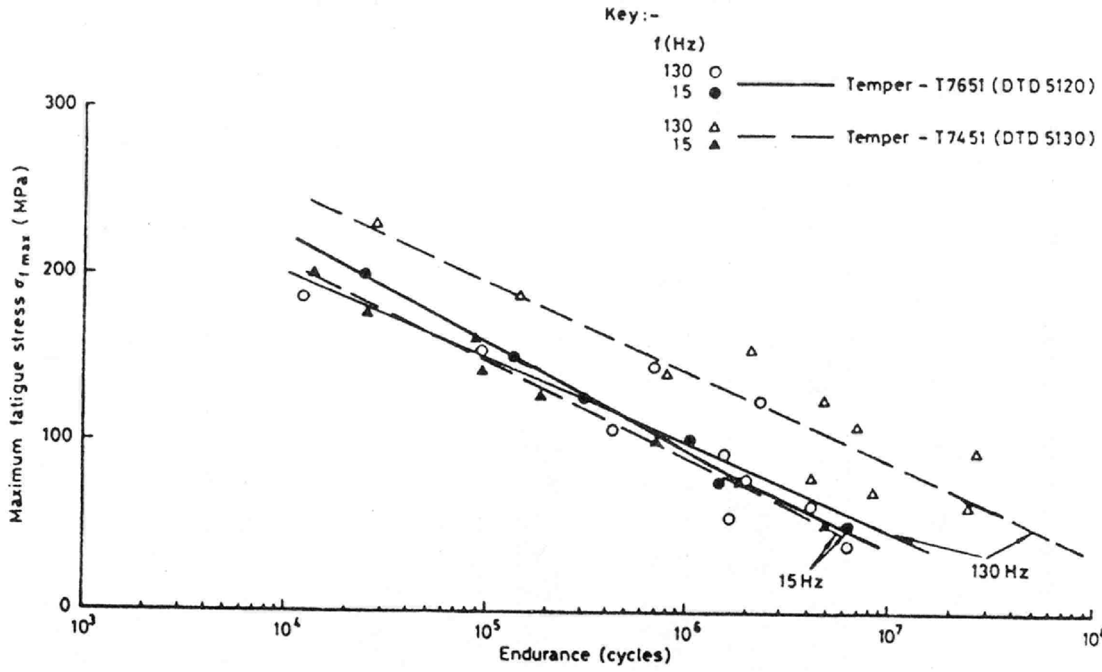

Fig. 5: Influence of Test Frequency [8]. Material 7010

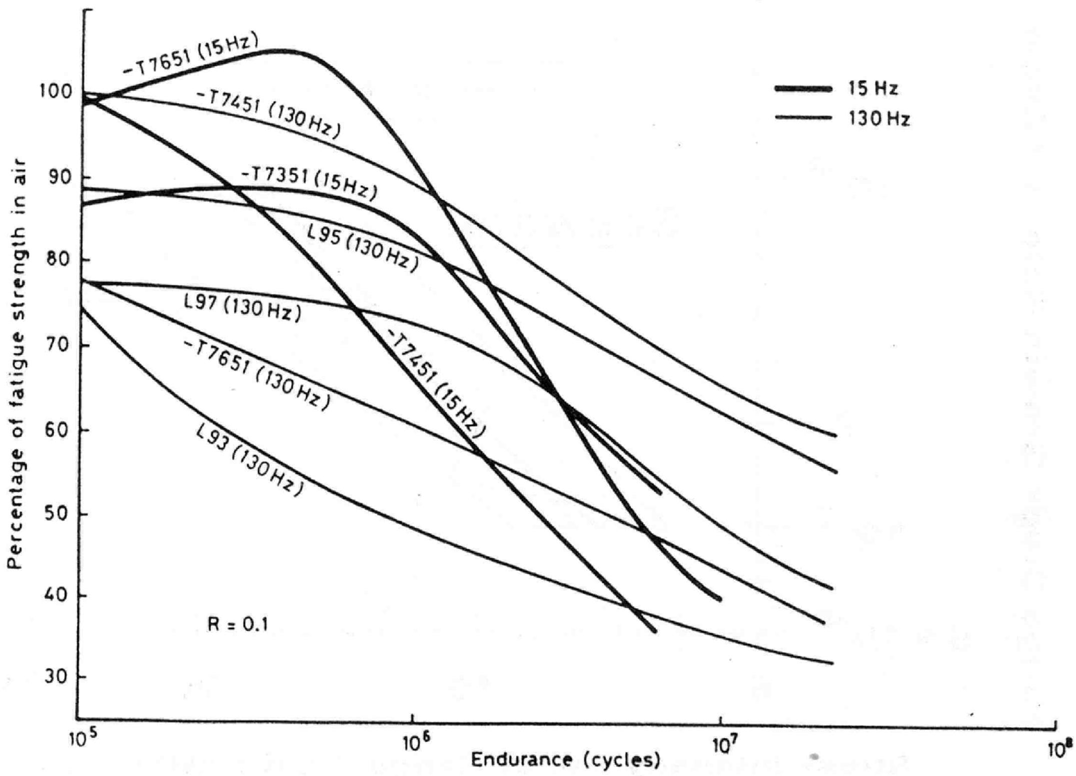

Fig. 6: Corrosion Fatigue Strength [32] of Al-Alloys

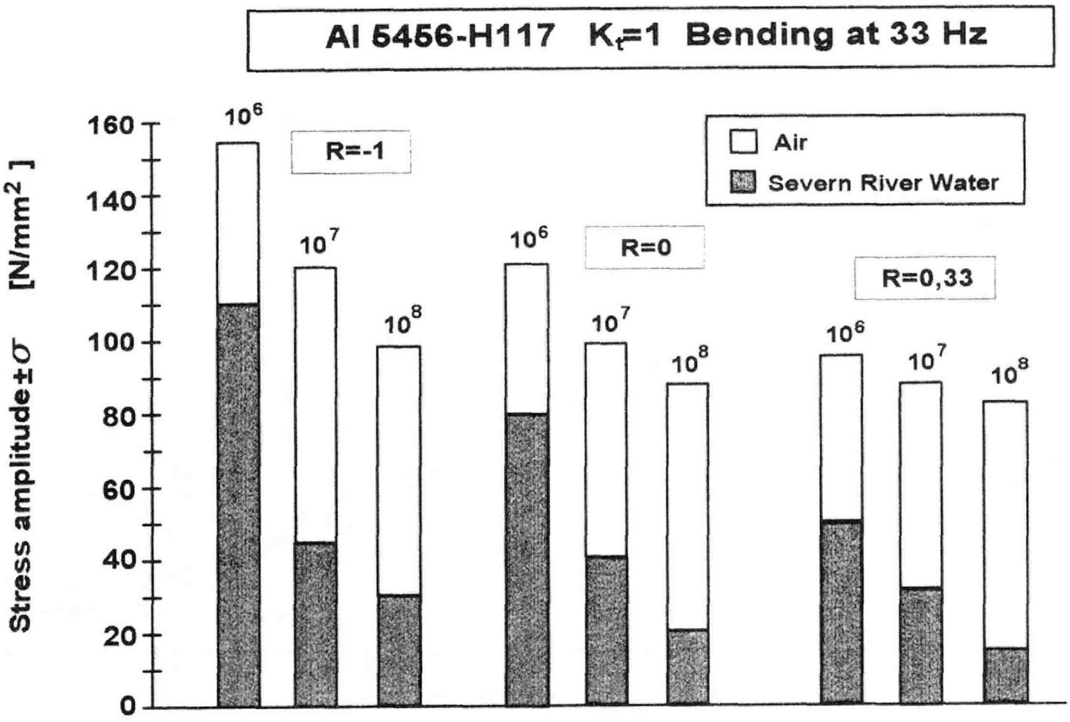

Fig. 7: Influence of Stress Ratio. "Marine" Al-Alloy [19]

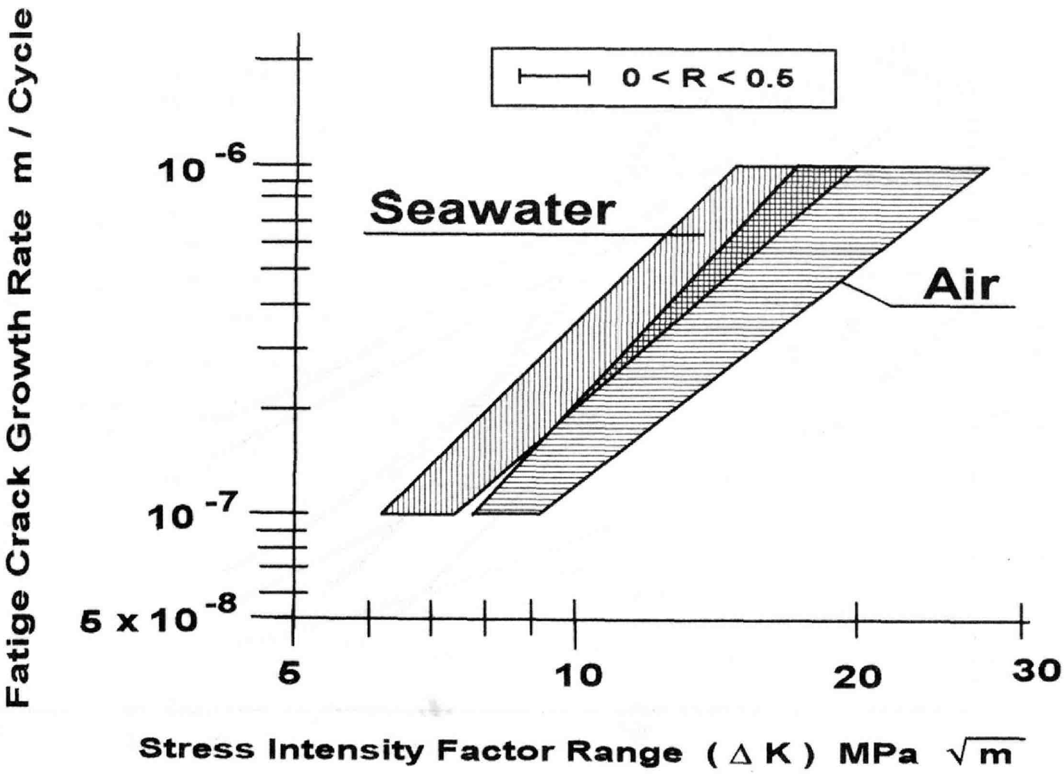

Fig. 8: Influence of Stress Ratio on Crack Growth [19]

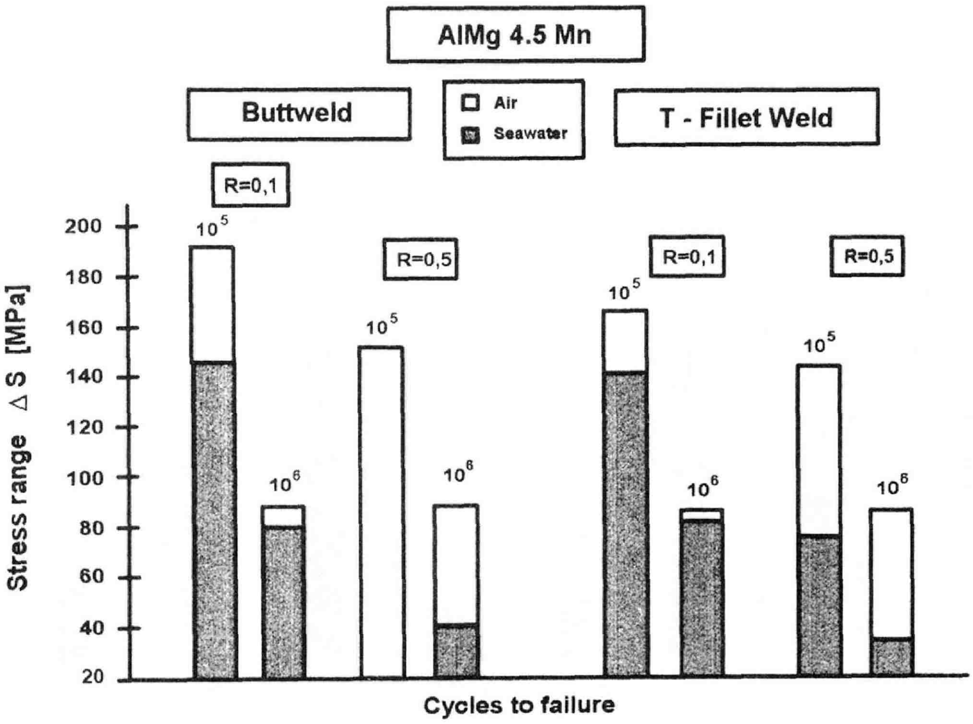

Fig. 9: Influence of Stress Ratio [22]

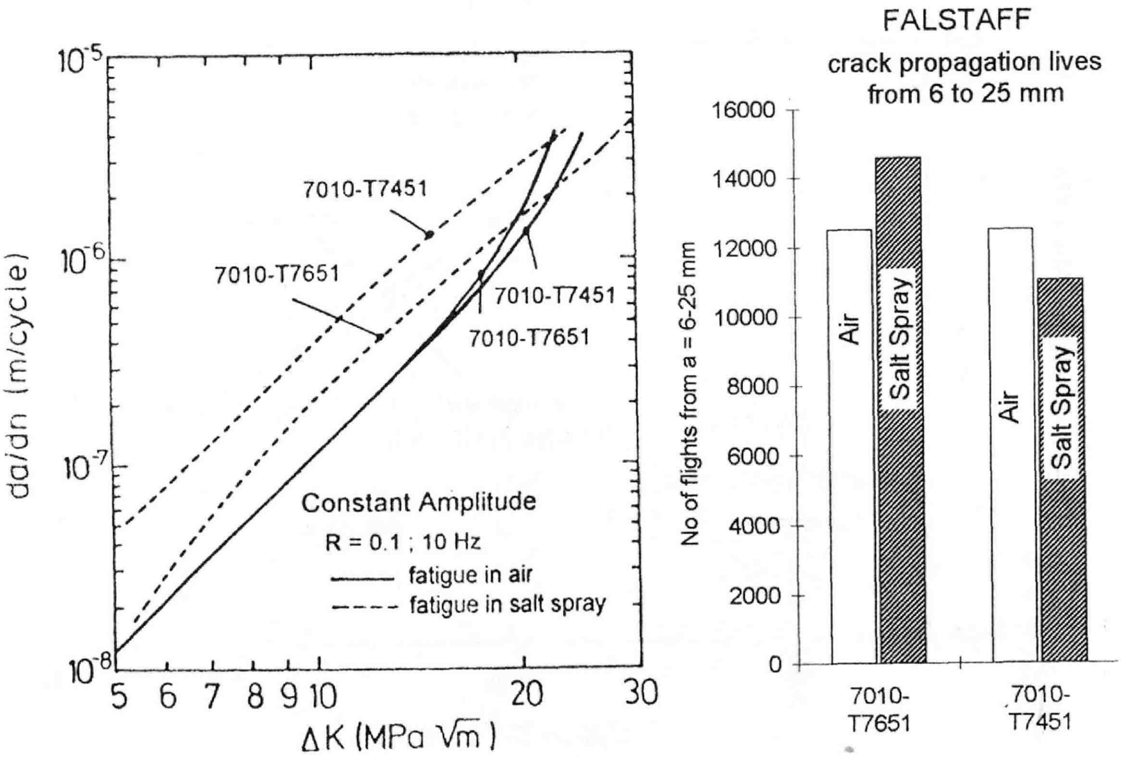

Fig. 10: Corrosion Fatigue Crack Growth under Constant and Variable Amplitudes [7]

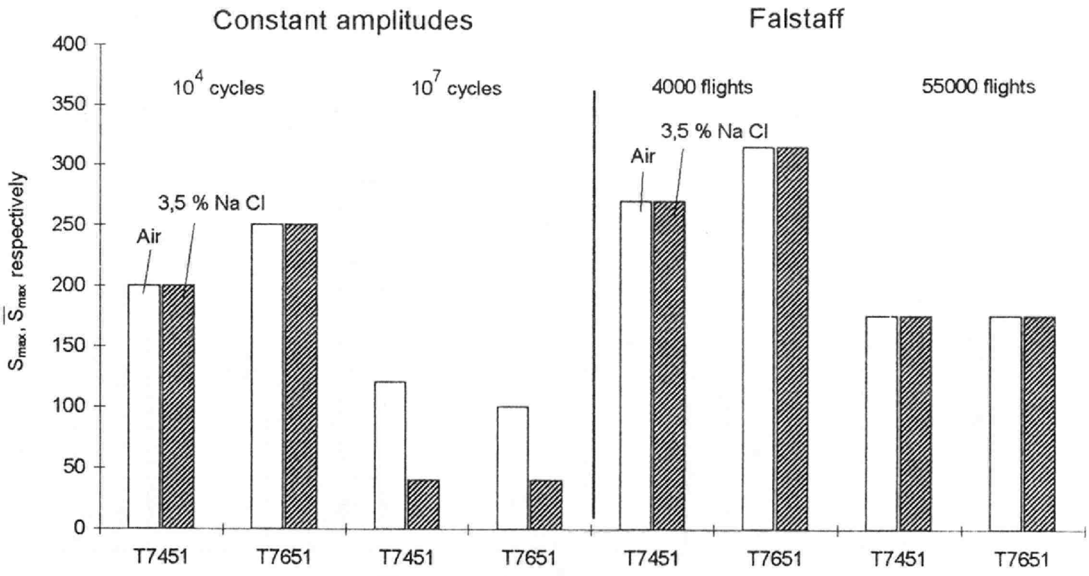

Fig. 11: Corrosion Fatigue Life under Constant and Variable Amplitudes [7]

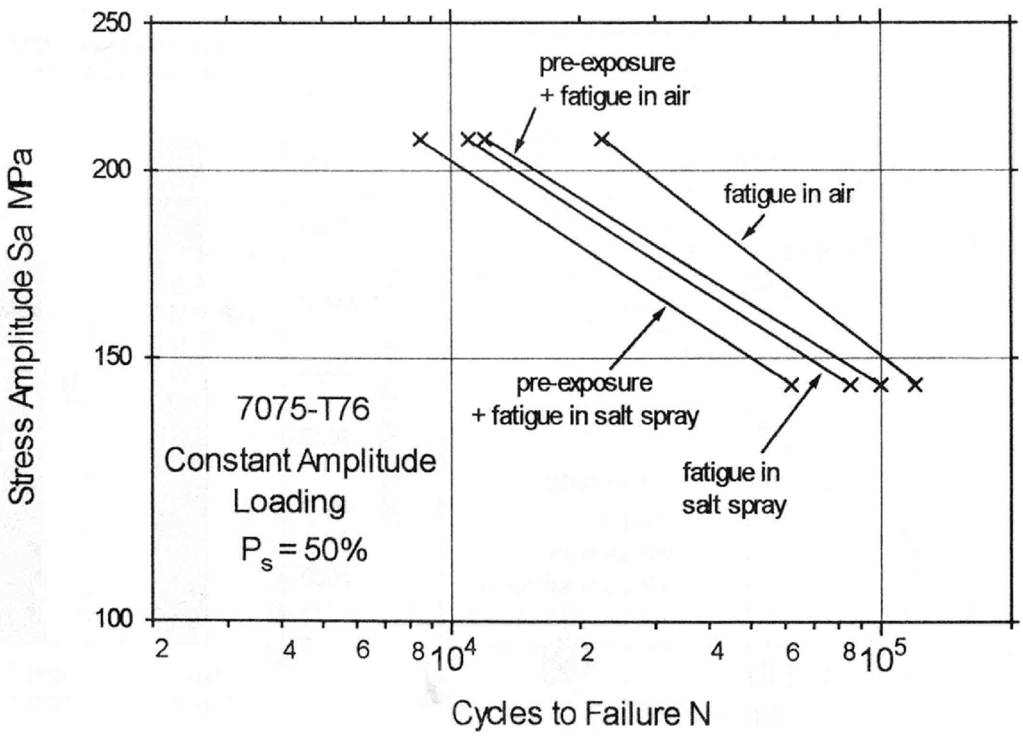

Fig. 12: Corrosion Fatigue Life of 1½ Dogbone Specimen under Constant Amplitudes [12]

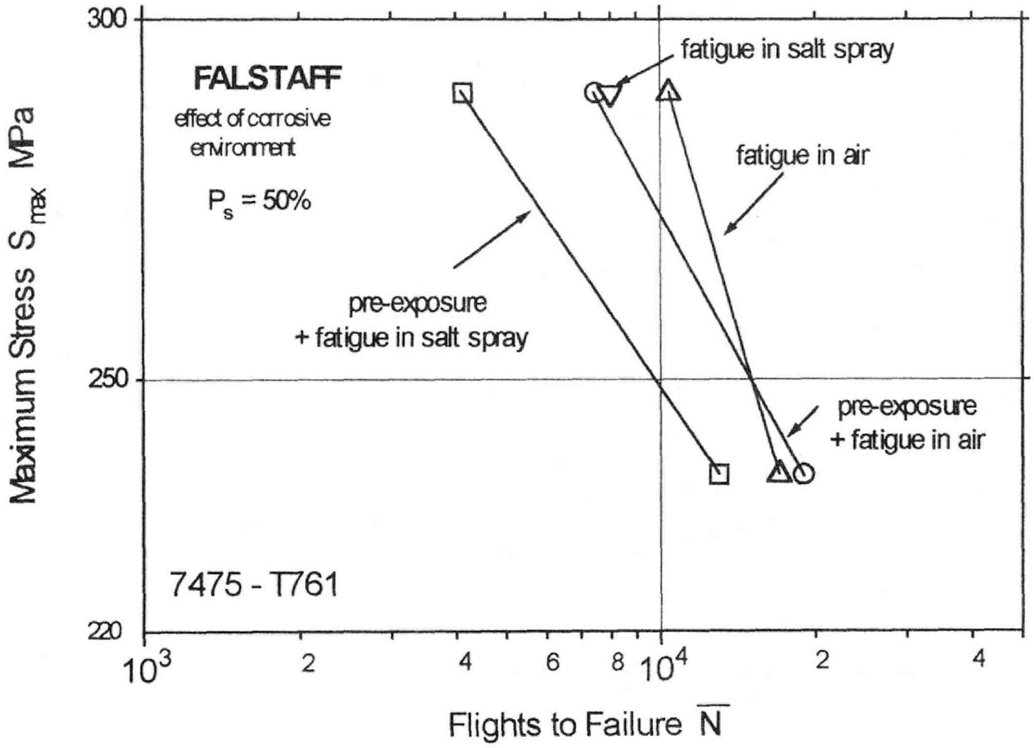

Fig. 13: Corrosion Fatigue Life of 1½ Dogbone Specimen under Variable Amplitudes [11]

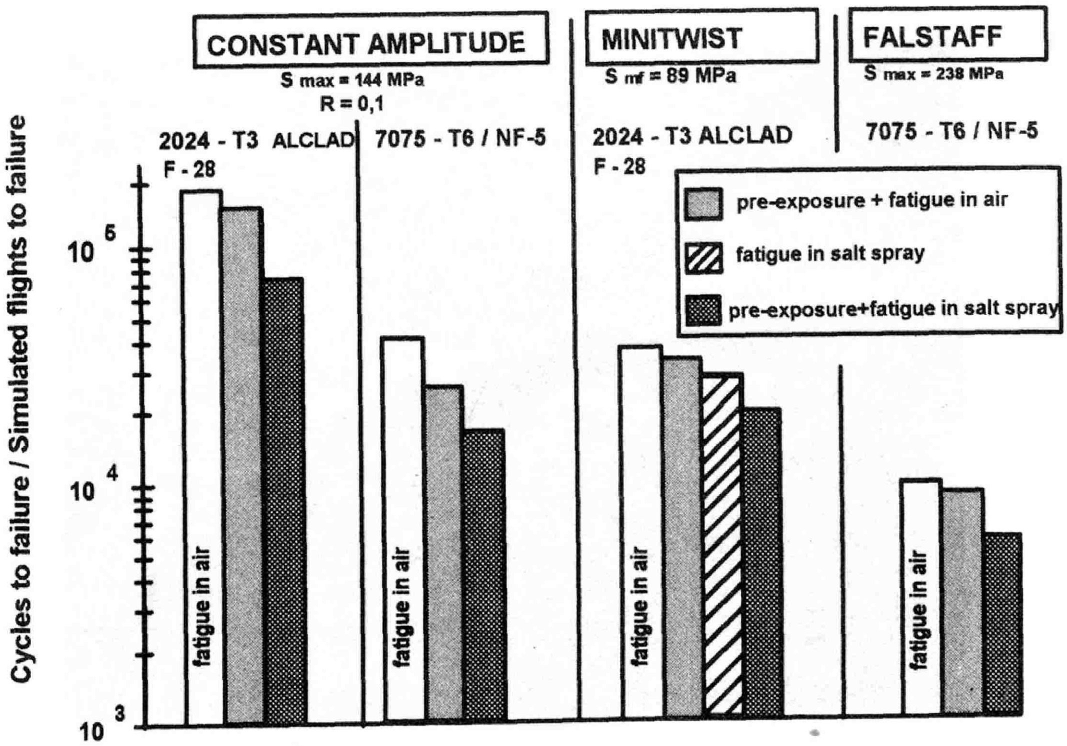

Fig. 14: Corrosion Fatigue Life under Constant and Variable Amplitudes [11]

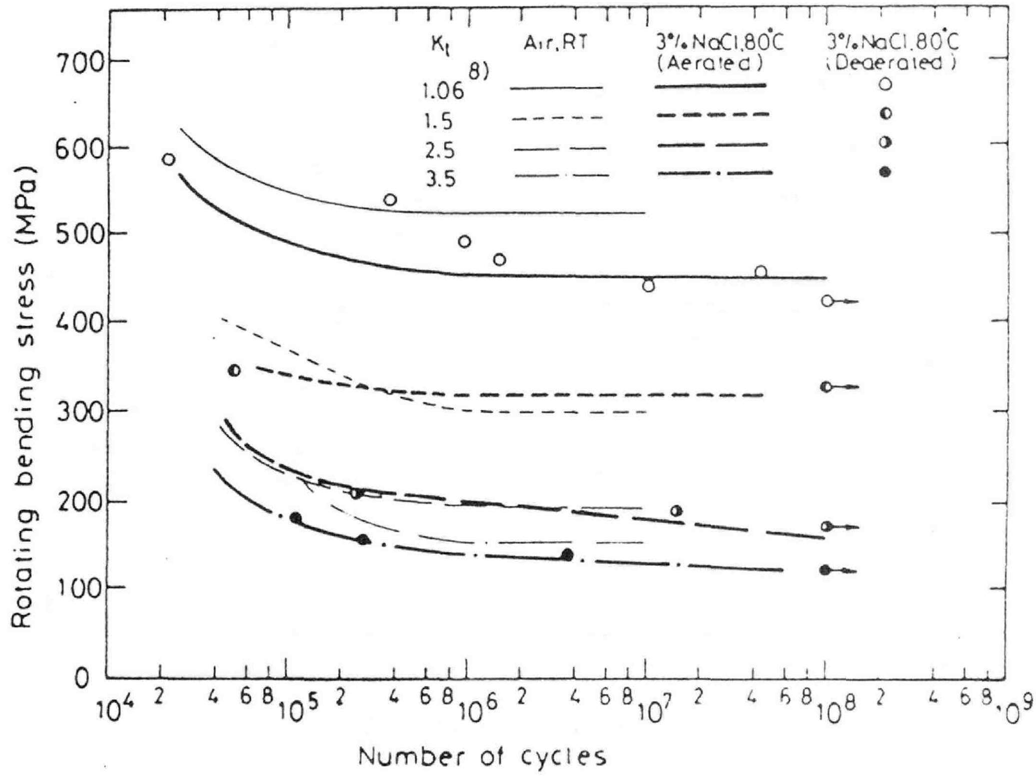

Fig. 15: Effect of Notches on Corrosion Fatigue Life of Ti6Al-4V [55]

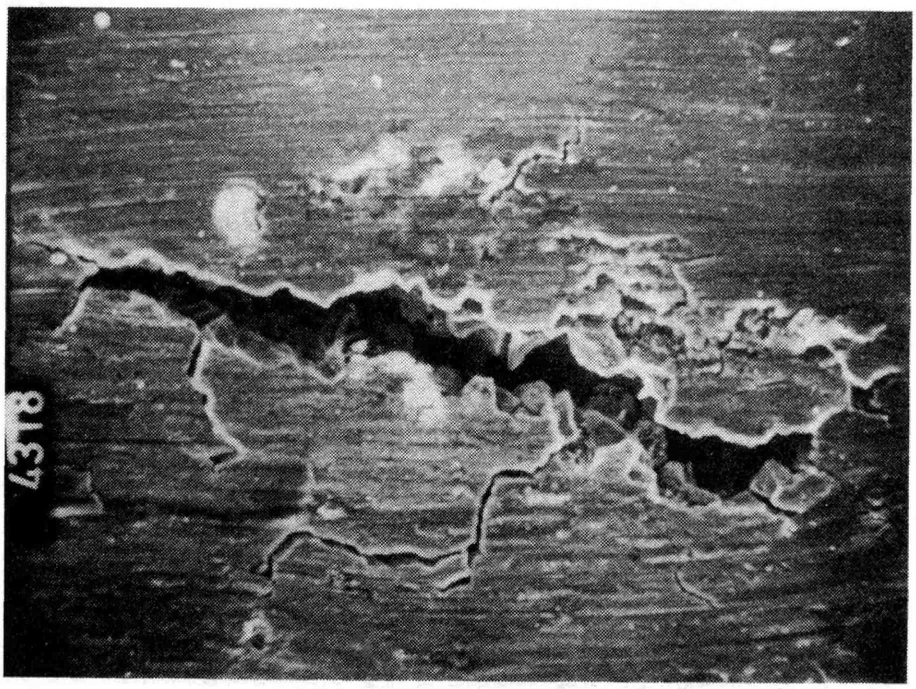

Fig. 16: Corrosion Pit. 7075-T6 Pit, Length 1,5 mm

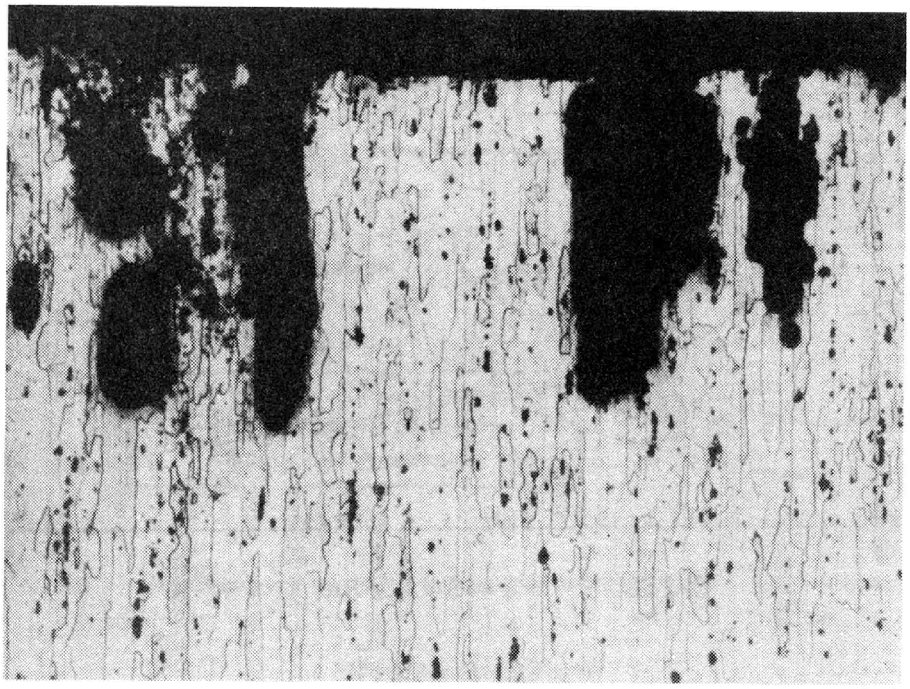

Fig. 17: Cross Section of the Pit of Fig. 16

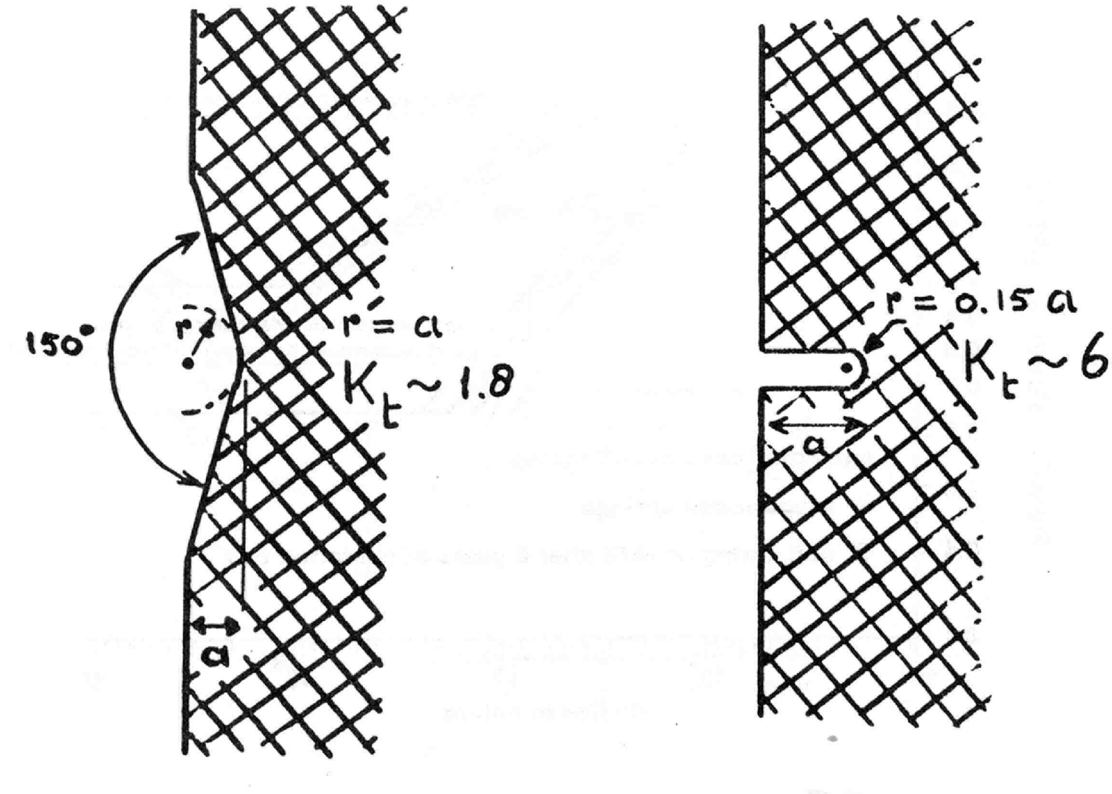

Fig. 18: Model of the Pit of Figs. 16/17

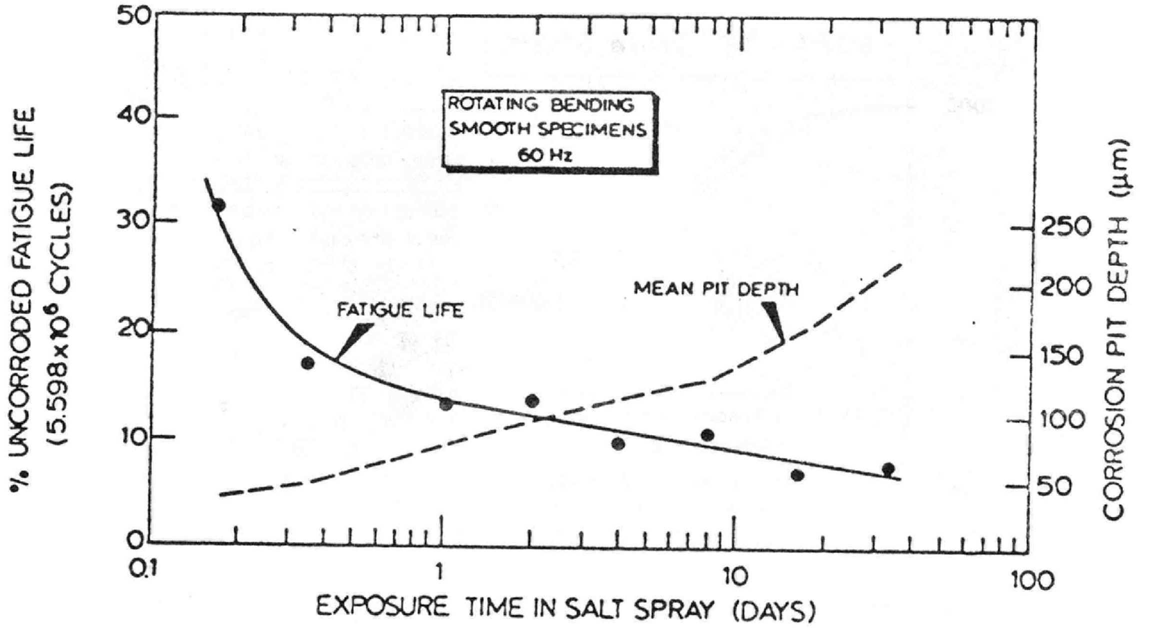

Fig. 19: Effect of Pit Depth on Fatigue Life [14]

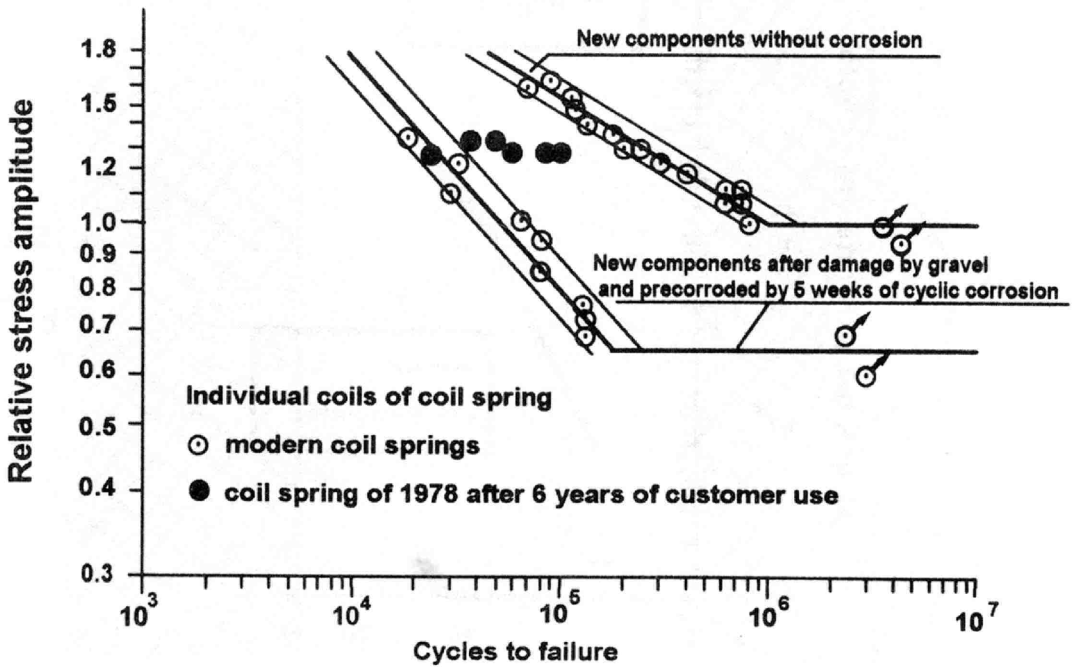

Fig. 20: Fatigue Life in Air and after Precorrosion [23, 46]

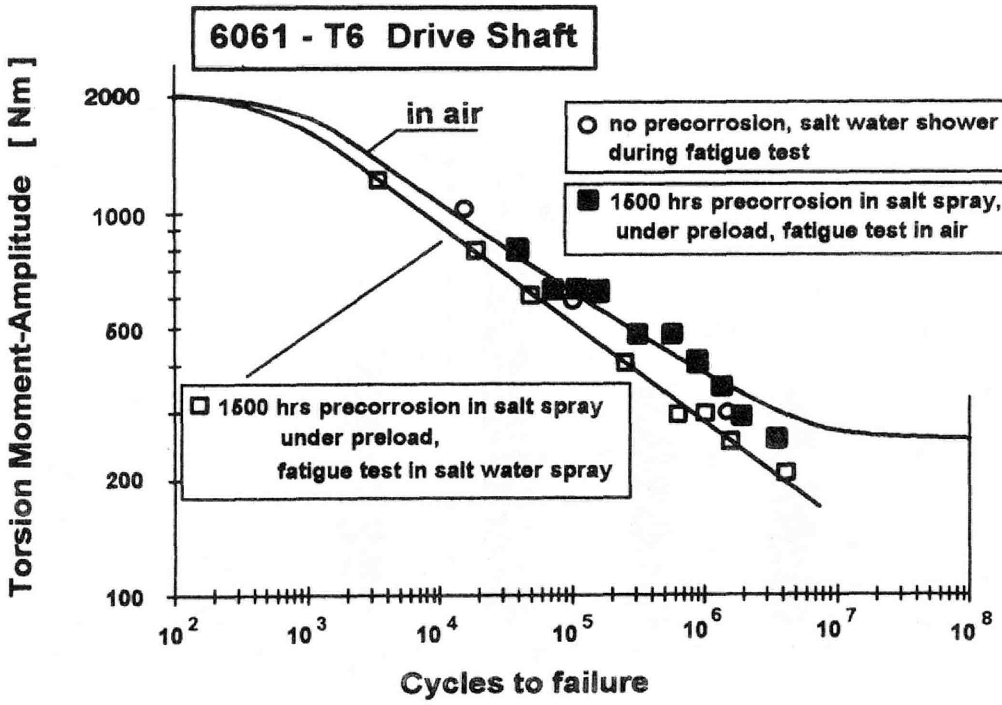

Fig. 21: Effect of Corrosion on Fatigue Life [61]

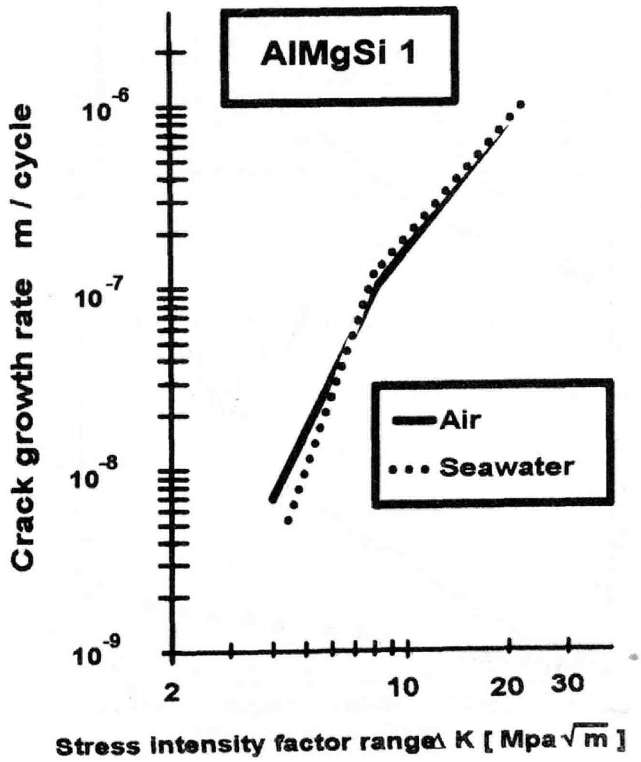

Fig. 22: Fatigue Crack Growth in Air and Seawater [21]

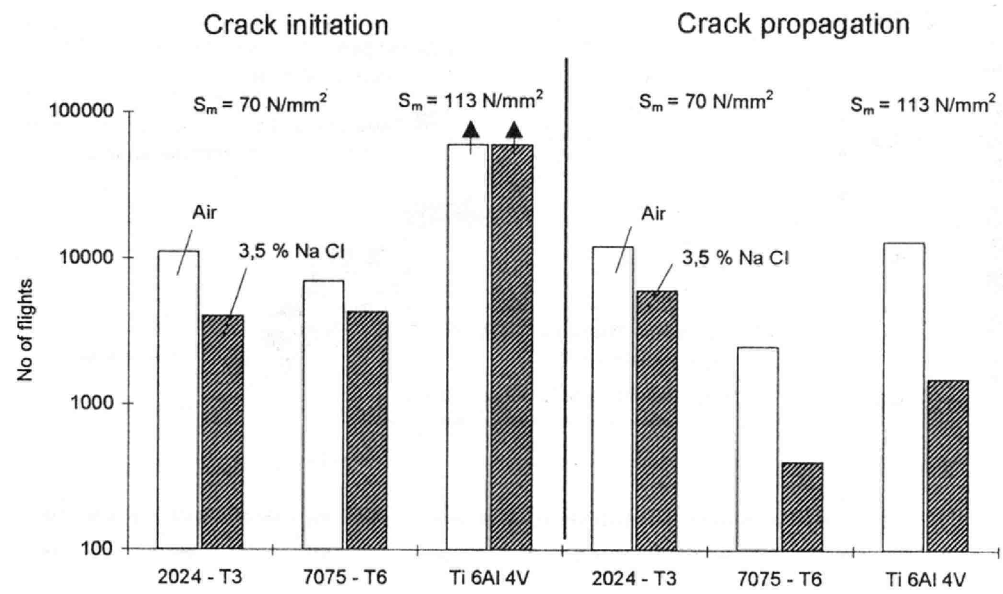

Fig. 23: Crack Initiation and Crack Propagation Lives. Twist Sequence [6]

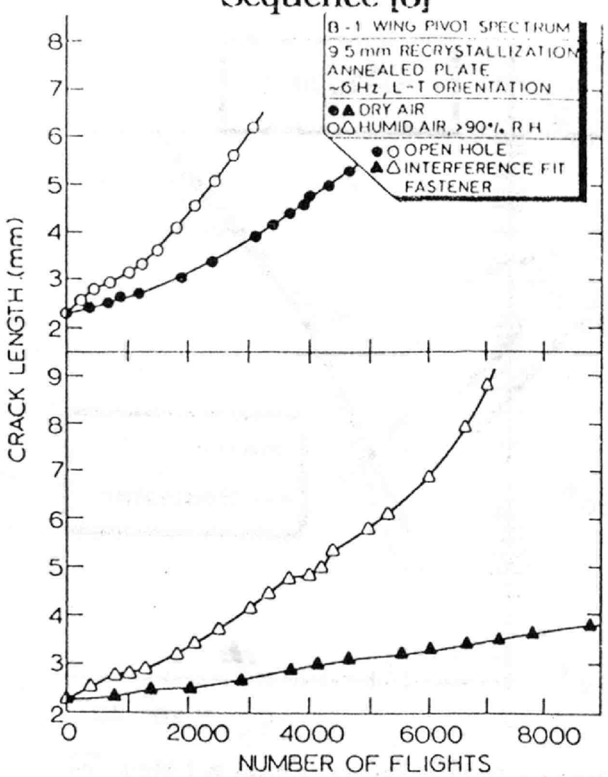

Fig. 24: Crack Propagation of Ti-6Al-4V. B-1 Wing Pivot Spectrum [83]

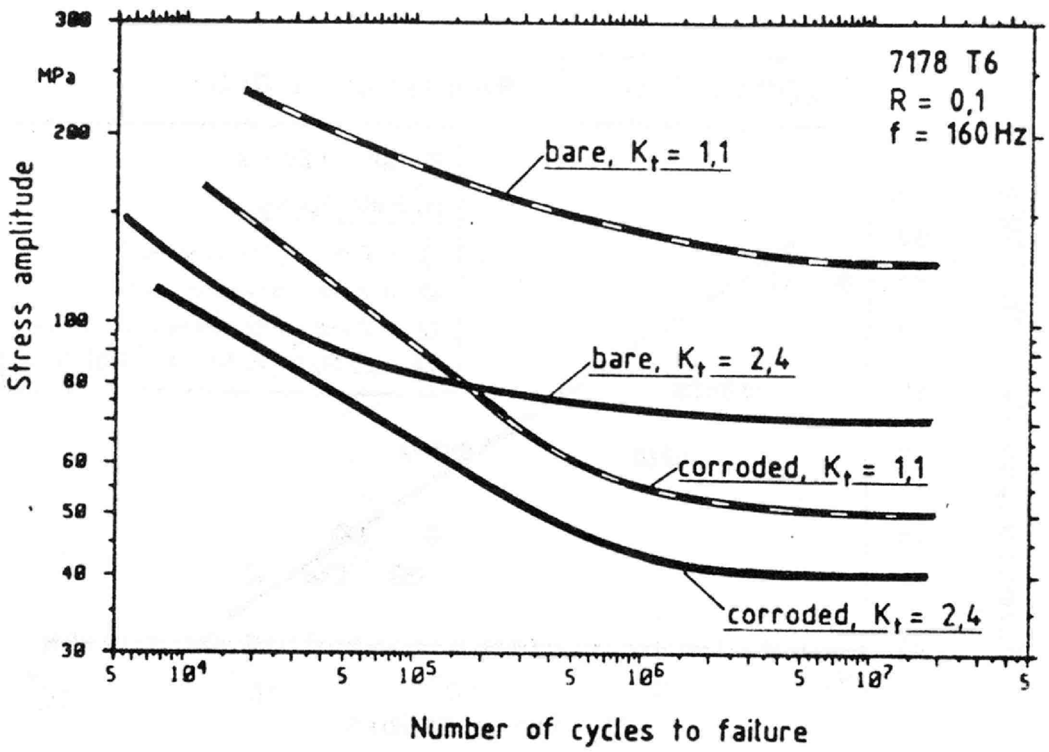

Fig. 25: Effect of Precorrosion in Service (10 years) on Fatigue Life in Air [86]

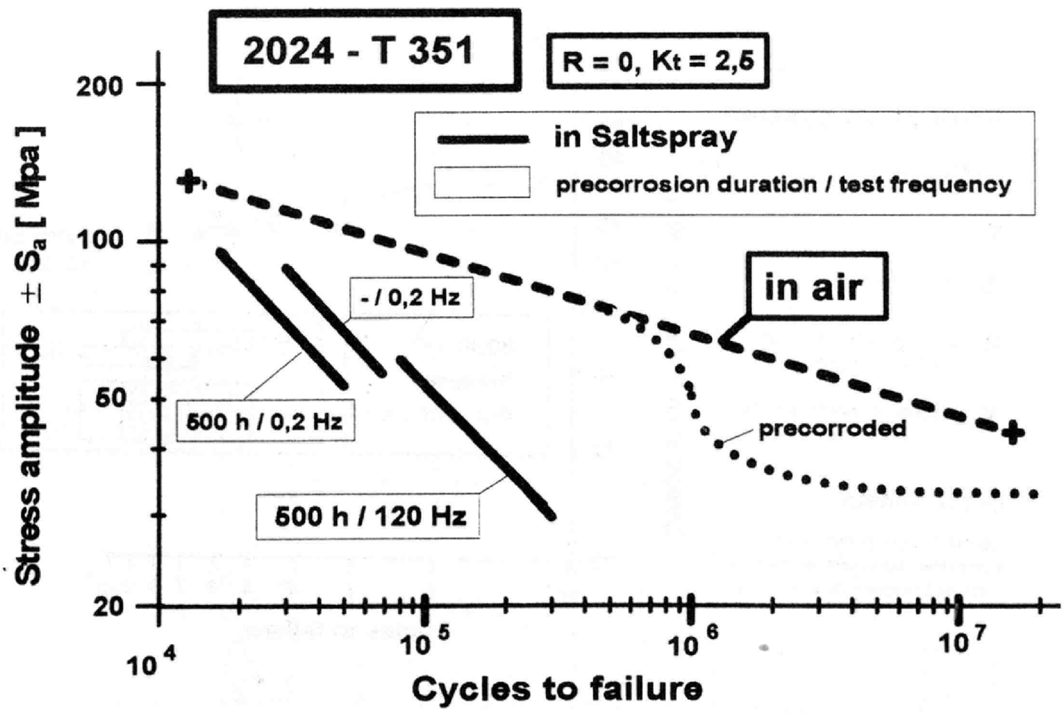

Fig. 26: Effect of Precorrosion in the Laboratory [86]

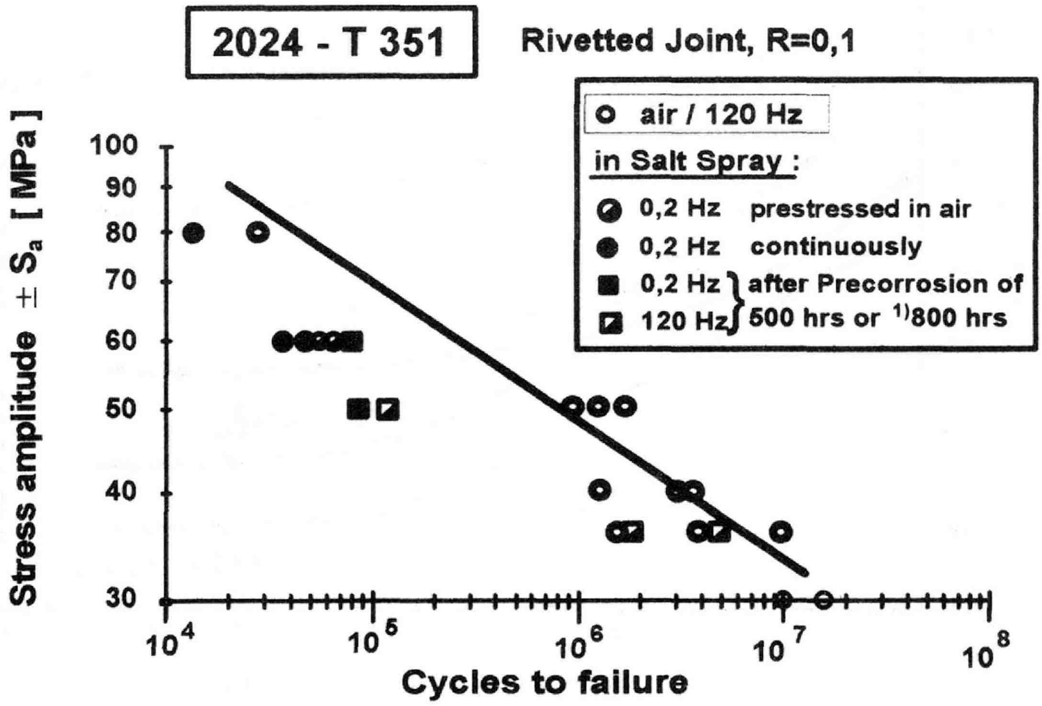

Fig. 27: Effect of Precorrosion and Fatigue in Salt Spray Rivetted Joint [86]

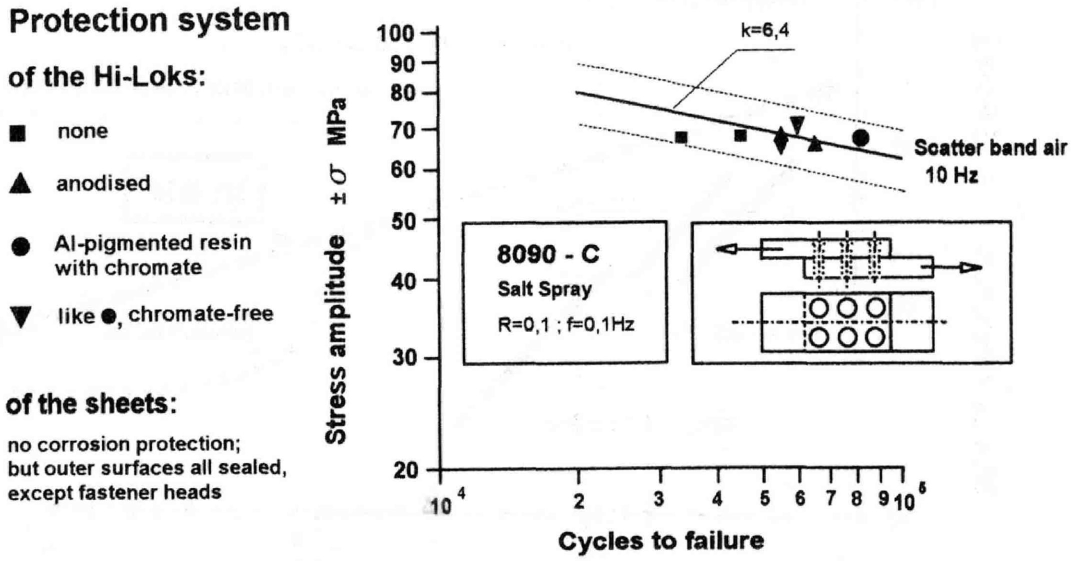

Fig. 28: Effect of Precorrosion and Salt Spray on Fatigue Life Rivetted Joint [98]

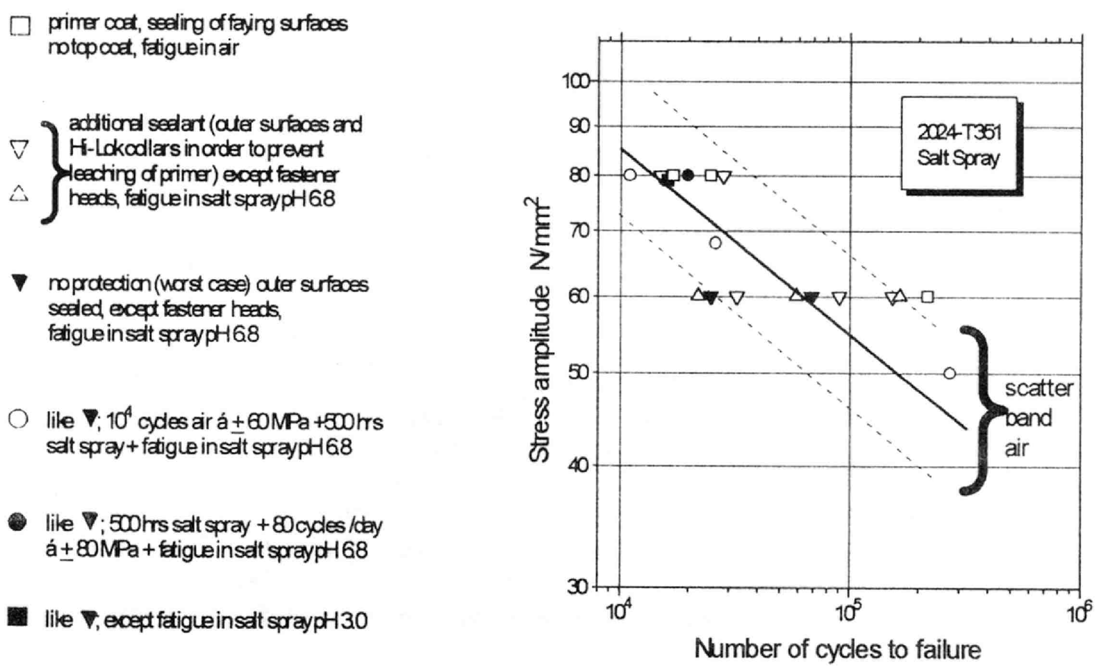

Fig. 29: Effect of Precorrosion and Salt Spray Rivetted Joint [98]

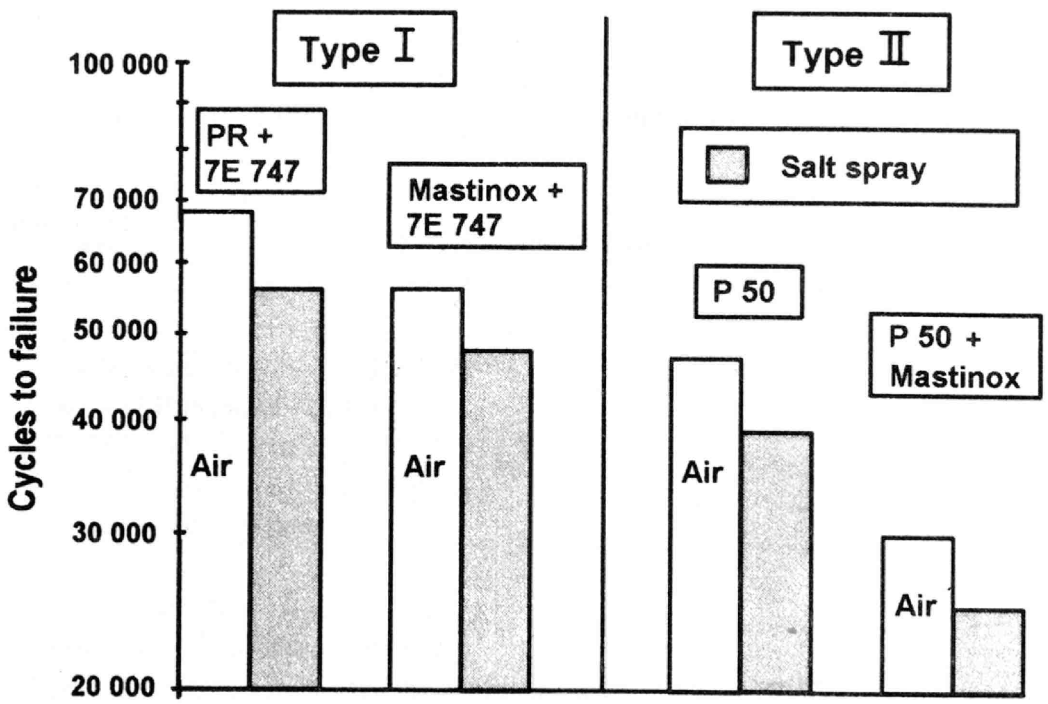

Fig. 30: Effect of Precorrosion on Fatigue Life [102]