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Occurrence of Corrosion in Airframes

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1. SUMMARY

Degradation of the mechanical properties of a material interacting with the environment is probably the best and widest definition for corrosion. In particular, as mechanical properties are the driving forces in the design of military aircraft, corrosion in airframes must be considered as a major problem because it directly affects safety, economic and logistic issues.

Considering the variety of materials, environments and mechanical stresses involved in the aeronautical field, it represents one of the areas where the largest spectrum of corrosion types is observed.

Many classification can be used to categorize aircraft corrosion phenomena: wet or dry corrosion depending on the environment, time dependent or time independent phenomena, mechanically or not mechanically assisted corrosion failures, etc.; all of them are useful to understand the main cause of the observed corrosion case and consequently to apply the most adequate corrective actions.

The purpose of this lecture is to provide an overview on the most common forms of corrosion experienced in the past, in order to present a wide range of severity arising from cosmetic to catastrophic failures.

Particular attention will be given to the corrosion aspects related with aging aircraft issues.

2. INTRODUCTION

Although aircraft corrosion is an old matter and many advances have already been done in corrosion prevention and materials selection science, nevertheless it seems far to be solved.

For instance, corrosion matter, that is a serious problem for every high engineered system, in airframes became more and more important in this last decade when aging aircraft subject was promoted by many different factors, most of them afferent to economic constraints[1].

Recently, corrosion contribution to the aging aircraft related costs has been estimated up to 80%.

On the other hand corrosion problems also have an heavy impact on safety and about 45% of the observed component failure can be ascribed to corrosion, when both direct and initiation effects are considered.

Corrosion in airframes is mainly an electrochemical matter, where an electrically conducting solution assists the transfer of metal ions, dry corrosion being almost always limited to engine components.

In spite of this limitation, a lot of different forms can be observed and one of the most useful theory that can be used to categorize them is the Structural-Electrochemical one[2].

In agreement with this theory, the driving force of an electrochemical corrosion process must be considered the presence of heterogeneity on the metal surface.

Depending on the nature and the dimension of this nonuniformity three different categories of corrosion must be experienced:

Uniform corrosion, in presence of sub-microstructural heterogeneity from 1 to 1000 Å, comparable to the cristallographic lattice dimensions (i.e. differences in the position of atoms, thermal fluctuations of metal ions in solution, etc.).

Selective corrosion, in presence of microscopic inhomogeneities from 0,1 m to 1 mm, comparable to the size of the cristallographic structure of the metal (i.e. grain boundaries, second phases in alloys, etc.).

Localized corrosion, in presence of macroscopic inhomogeneities greater than 1 mm, comparable to the size of the component (i.e. galvanic coupling, differential aeration, etc.).

3. UNIFORM CORROSION

Here, the inhomogeneities on the metal surface interacting with an aggressive environment, are so small in dimension and potential that the same area will change, playing continuously a different anodic and cathodic role.

Paper presented at the RTO AVT Lecture Series on “Aging Aircraft Fleets: Structural and Other Subsystem Aspects”, held in Sofia, Bulgaria, 13-16 November 2000, and published in RTO EN-015.

The total effect is an attack on the whole surface leading to a uniform or quasi-uniform lost in depth of the metal.

Although this is a very common mechanism in many corroded systems, it is not so often observed on airframes because the chosen aeronautical materials are always less prone to it.

Uniform corrosion is usual for non-stainless steel and iron where it can be easily recognized by red rust.

Being easily detected and forecasted uniform corrosion can't be considered as a very dangerous form of corrosion.

Usually general attack occurs on parts where the original protective coating has failed for any reason. The most typical case is certainly observed on cadmium plated steels after the anodic coating has been totally sacrificed (Fig. 1).

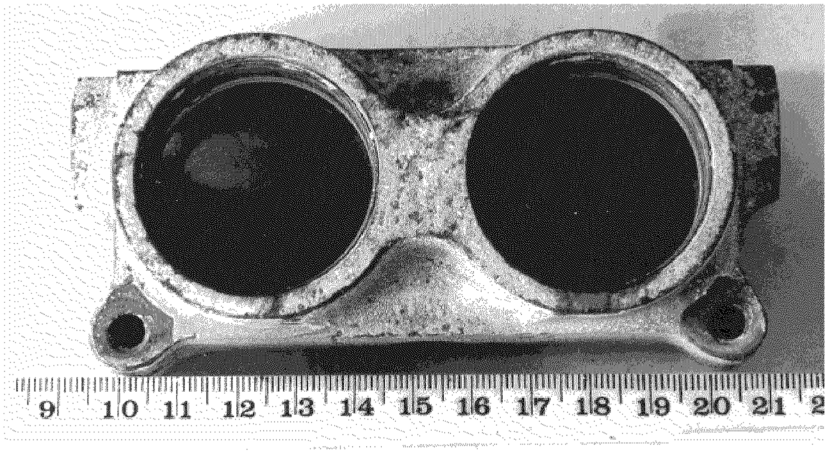

Fig. 1 – Uniform Corrosion on a cadmium plated AM-X Air Combustion Chamber

Erosion, caused by the action of a fast moving fluid, can also lead to a uniform or quasi-uniform attack. This specific mechanism, called erosion-corrosion, becomes more severe in aircraft operating in hot desert climates, where an high humidity content, especially in night time, is associated with sand: the solid particle content, furthermore rich in salt, acts as an extremely abrasive media, removing paint, surface finish and corrosion products, offering continuously new metal surface.

Aging aircraft issues exacerbate uniform corrosion problems on electrical and avionics equipment where, in order to obtain the requested performance, materials are often inferior in terms of corrosion resistance.

4. SELECTIVE CORROSION

In this category are included all the phenomena depending on the presence of heterogeneities in chemical composition. In this sense we can also talk about this electrochemical attack as caused by an intrinsic heterogeneity of the material.

4.1 Intergranular Corrosion

On airframes, intergranular corrosion (Fig. 2) is the more often observed mechanism of this class because it is characteristic for the aluminum alloys, both the Al-Cu (2xxx) and the Al-Zn (7xxx) alloys, where the driving force for the electrochemical process is the difference in potential between the second phases (richer in copper - more noble -, or richer in zinc – less noble -) and the aluminum matrix.

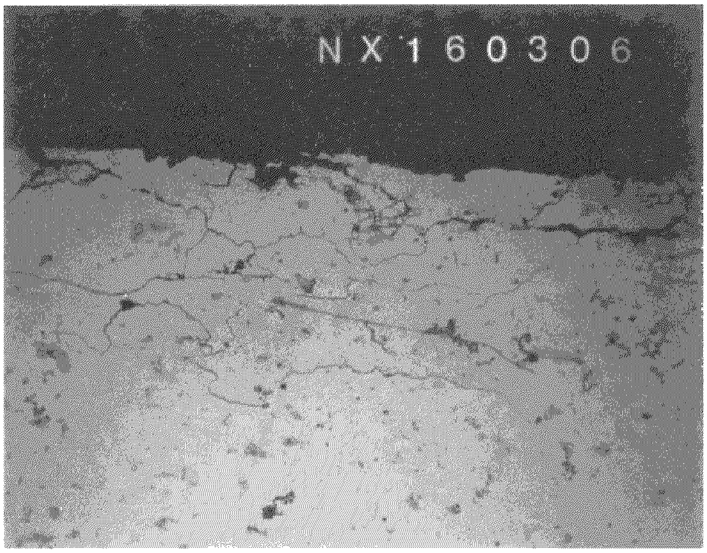

Fig. 2 – Intergranular Corrosion on AA2024 (160x)

In this case corrosion profile follows the shape of grain boundaries (Fig. 3), where second phases are precipitated, and must be considered very dangerous because, in spite of a minimum material lost, mechanical properties fall dramatically down[3]. Furthermore, intergranular corrosion is frequently hard to detect also by means of NDE.

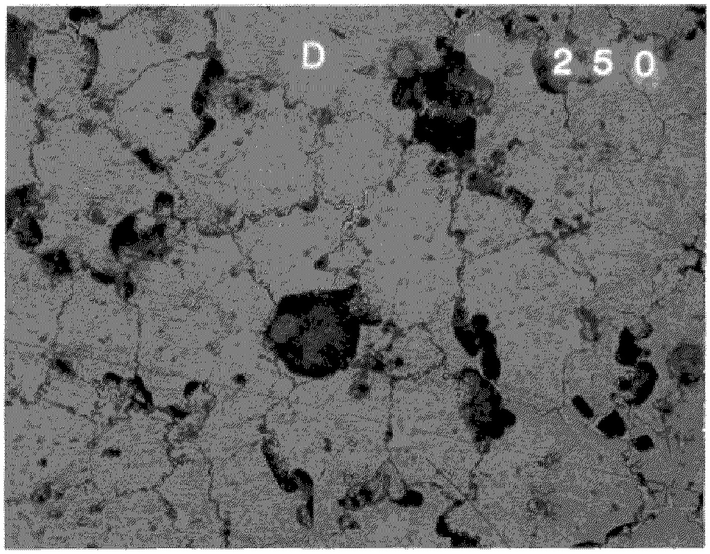

Fig. 3 – Intergranular Corrosion on Mg Alloy AZ-91C (250x)

When intergranular corrosion occurs on heavily rolled or extruded parts having elongated grains in the direction of working, the produced phenomenon has the very characteristic aspect of an exfoliation (Fig. 4).

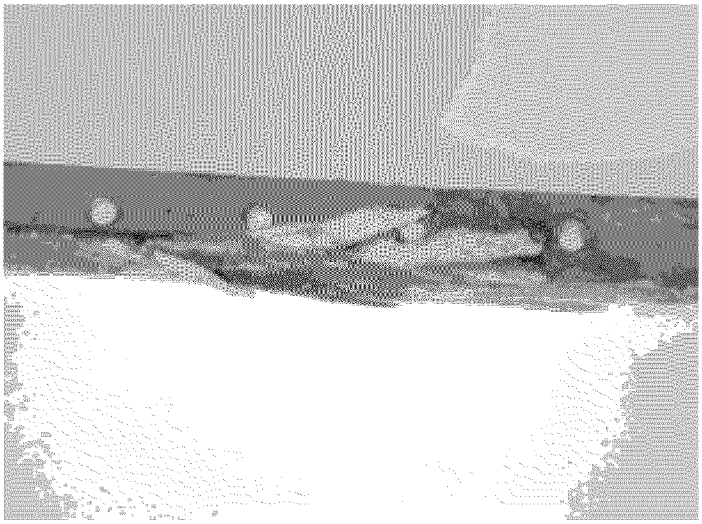

Fig. 4 – Exfoliation on a Breguet Atlantic Br.1150 AA2024 spar

Intergranular attack can also be observed on austenitic stainless steel. On these materials an incorrect cooling procedure after an heat treatment can lead to a sensitization of the part, caused by the grain boundary precipitation of chromium carbide ($Cr_{23}C_6$) and according to this the strong depletion in chromium content of the contiguous areas. This can be the case of wrong welding procedures (Fig. 5).

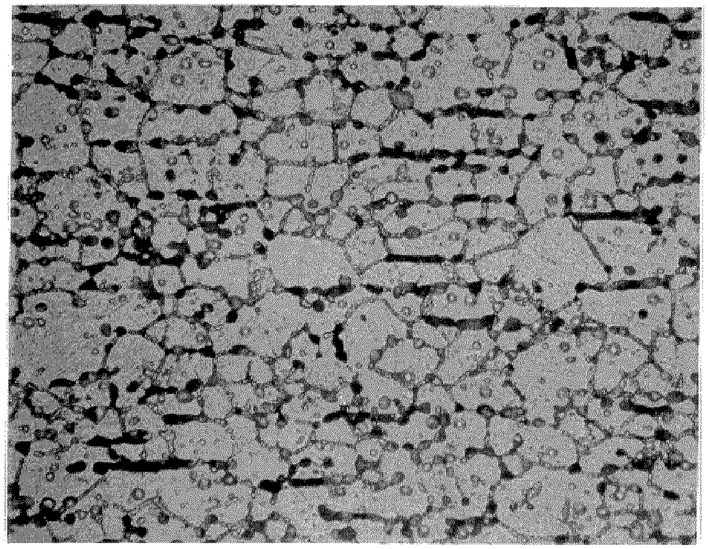

Fig. 5 – Low Temperature Sensitization on a PH 17-7 Stainless Steel

4.2 Crystallographic Corrosion

Although much less common on airframes, another kind of selective attack to be mentioned is the crystallographic corrosion which can be generated when whole grains or volumes are each other electrochemically different enough.

This is the case of some brasses where parts richer in zinc leave the metal leading to a spongy structure.

5. LOCALIZED CORROSION

This is certainly the class where the widest number of corrosion mechanisms are observed.

The common factor among the different forms of corrosion in the case of a localized attack is the presence of stable and clearly separate cathodic and anodic areas.

5.1 Pitting Corrosion

Pitting corrosion is a dangerous attack which occurs on passive materials when the protective oxide layer breaks.

It is often observed on stainless steel and aluminum alloys that spontaneously form a protective film: as a result of small damages on the passive layer, the damaged areas will work as anodes immersed in a very large cathodic area and will suffer in consequence of this a very localized attack which leads to the formation of deep and narrow cavities.

Pitting corrosion is particularly common on aircraft structures operating in marine environments, since the chloride ions and halide ions in general promote the local dissolution of protective oxide films.

Here following (Fig. 6 and 7) some cases occurred in the recent past are shown.

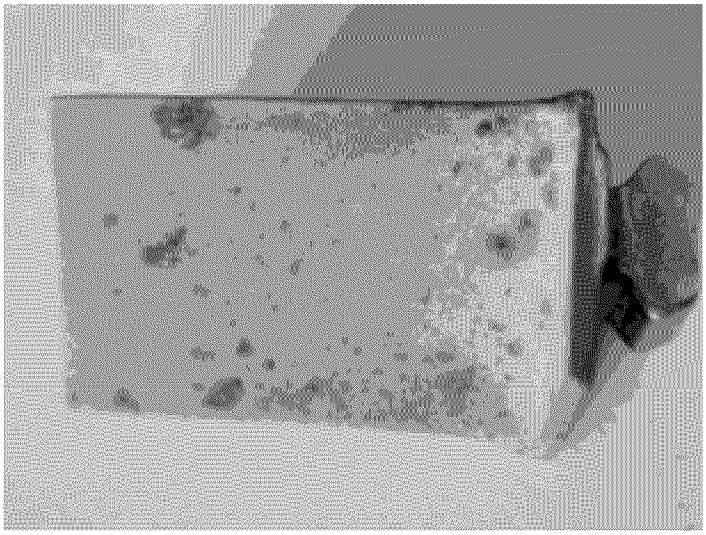

Fig. 6 – Pitting Corrosion on a HH-3F Compressor Blade

Fig. 7 – Pitting Corrosion on MB-326 Balance Tabs

Some authors[4] include in pitting corrosion mechanism also those corrosion phenomena that take place on active metals, previously protected by a suitable external coating, when the protection is locally damaged.

In any case pitting must be considered very insidious since it tends to accelerate its corrosion rate because of the increasing acidity and chloride content inside the cavity; furthermore, in highly loaded structures, the stress concentration at the base of a pit is often sufficient to promote fatigue or stress corrosion cracking.

5.2 Crevice Corrosion

This form of attack (Fig. 8) is originated by the difference in the concentration of dissolved oxidant agent (usually oxygen) inside and outside a crevice. In this case the area inside the crevice will act as anodic and there a pit will develop.

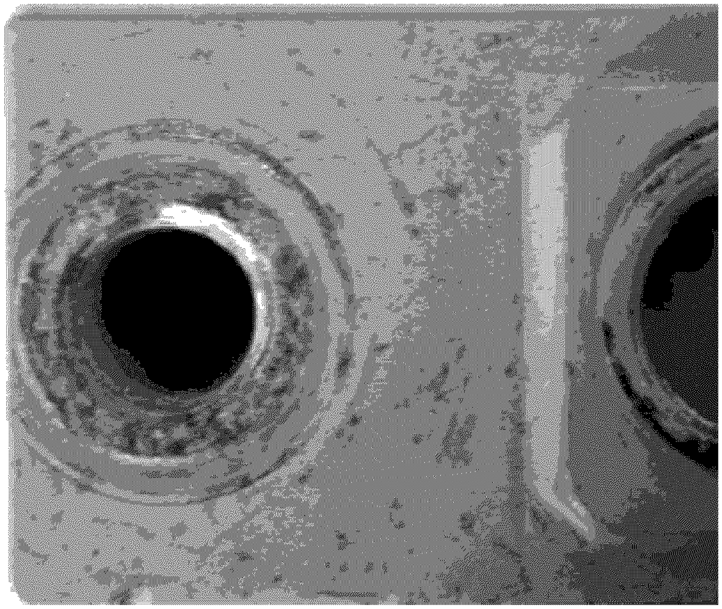

Fig. 8 – Crevice Corrosion on Tornado

In airframes, corrosion crevice is frequently observed on lap joints or under surface deposits in presence of stagnant solution. It is usually associated with a poor performance of the sealant or sometimes can be caused by a defect of design (i.e. poor drainage conditions).

Its nature makes it dangerous because often occur on unexpected areas and can't be detected by visual inspection if not disassembling.

5.3 Galvanic Corrosion

Galvanic corrosion is the most evident form of localized attack, where anodic and cathodic areas are very clearly identified.

It occurs when two metals of different electrochemical potential are in contact in a corrosive medium and the resulting damage to the less noble metal will be more severe than if it was exposed alone to the same medium.

The extension of the corroded area on the anode as far as the corrosion rate will depend on the difference in the electrochemical potential between the metals and the conductivity of the aggressive medium. Anyway, the corrosion attack will be more concentrated in the part of the anodic metal closest to the cathode.

In aircraft structures is often necessary to use different metals and galvanic corrosion can't be completely avoided. In this case is important to take care about the ratio between the cathode and the anode: increasing the ratio the corrosion will tend to be superficial.

This is the typical example occurring at fastener holes in aluminum alloy skin when steel bolts or rivets are used.

Looking at the galvanic series it's easy to realize that magnesium alloys are very susceptible to suffer galvanic attack when used in junction with any other metal (Fig. 9-11).

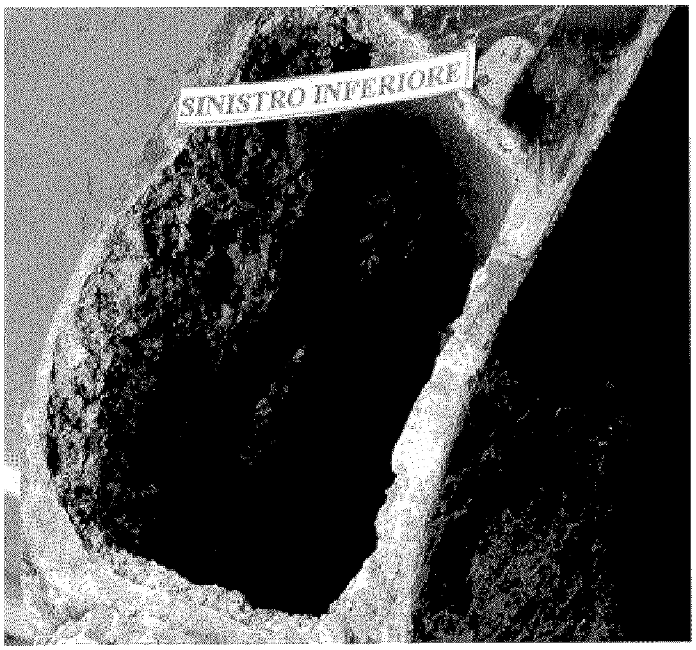

Fig. 9 – Galvanic Corrosion on a Mg Alloy Spacer, coupled with a steel beam in the MB-326 Central Section

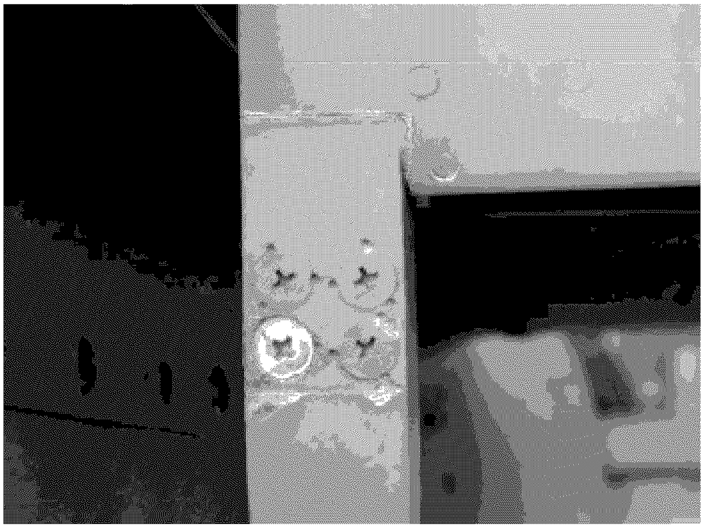

Fig. 10 – Galvanic Corrosion on the MB-339 between Mg Alloy Trim and Aluminum rivets

Fig. 11 – Galvanic Corrosion on the MB-339 Attach Fitting

5.4 Filiform Corrosion

Filiform corrosion (Fig.12) can be found under organic coatings such as paints, due to penetration of moisture through the coated surface under specific temperature (T ≥ 30 °C) and humidity conditions (Hr ≥ 85%).

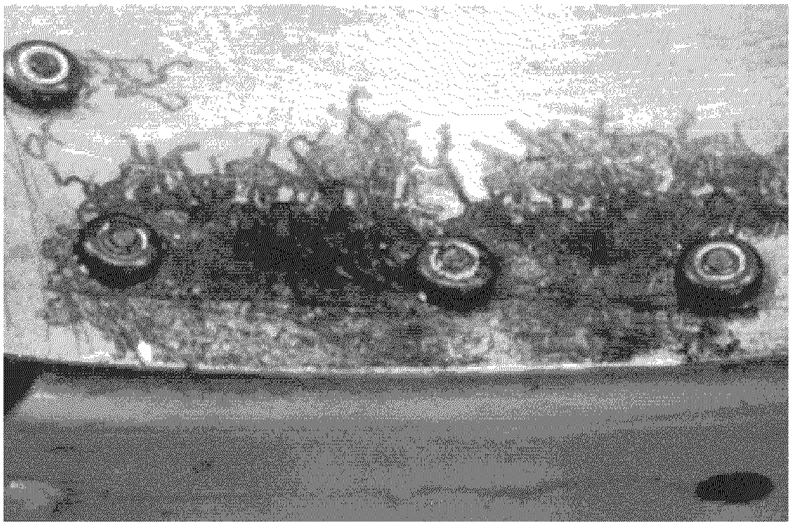

Fig. 12 – Intergranular Corrosion on Aluminum Alloy

This mechanism is not particularly dangerous on itself since it propagates creating blistering "wires" of corrosion products on the surface of the metal, actives just on the tip of each wire, but can degenerates in more serious attacks if not detected and removed in an early stage.

5.5 Stress Corrosion Cracking (SCC) and Corrosion-Fatigue

These two dangerous localized corrosion mechanisms are often unfortunately observed on airframes.

Both produce cracks, different in shapes and patterns, whom growth is caused by the synergetic action of a moderate corrosive environment and a mechanical stress: a static load (lower than the material's yield tensile stress) in the case of SCC (Fig. 13), or a cyclic load in the case of corrosion-fatigue (lower than the material's fatigue limit).

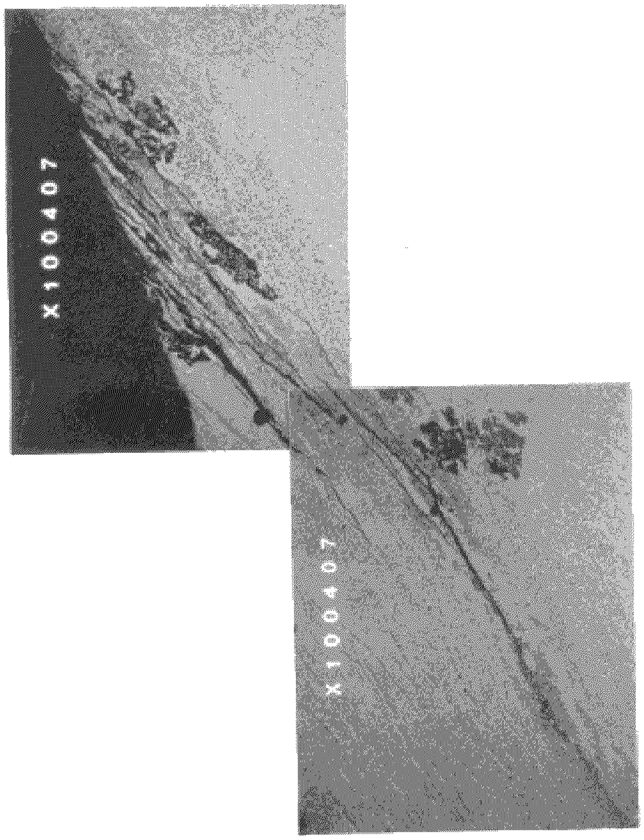

Fig. 13 – Stress Corrosion Cracking on a Br.1150 bomb bay guide rail

Many models have been proposed[5] to explain the crack growth process for these attacks, all of them coinciding that just the crack tip is anodic while the rest of the metal (including the walls of the crack) act as cathodic.

Once the crack has formed it will continue to grow, stopping only when the static (SCC) or the cyclic (corrosion-fatigue) load has fallen below the critical value, or alternatively excluding the corrosive environment.

These forms of corrosion must be considered as a major problem in aging airframe related issues, particularly corrosion-fatigue at low frequency cyclic stresses, where the time dependent corrosion process has the opportunity to explicate its action.

In effect Multiple Side Damage, a phenomenon under intensive investigation since the last ten years, can often be seen as an extension of the corrosion-fatigue mechanism.

5.6 Hydrogen Embrittlement

Hydrogen embrittlement is often considered as a special case of the more general SCC mechanism[6].

Its effect is to lower the ductility in metals when penetrated into the material[7] by means of a natural corrosion reaction or, more often, during a plating or a pickling process.

High strength steel and austenitic stainless steel are the most commonly affected aerospace materials, their susceptibility also depending on the metal composition[8].

Parts more often failed for hydrogen embrittlement are bolts and main landing gear items.

5.7 Fretting

Fretting is an insidious form of corrosion that occurs when the environmental action is assisted by material wear under low vibratory relative mote of parts.

The abrasion of the surface finishing, and after that of the corrosion products, continuously offer new metal surface to the environmental aggressive attack: because of the abrasive nature of the corrosion products, this mechanism is rate increasing, usually leading to hemispheric pits where fatigue marks are often found on their bottom (fig. 14).

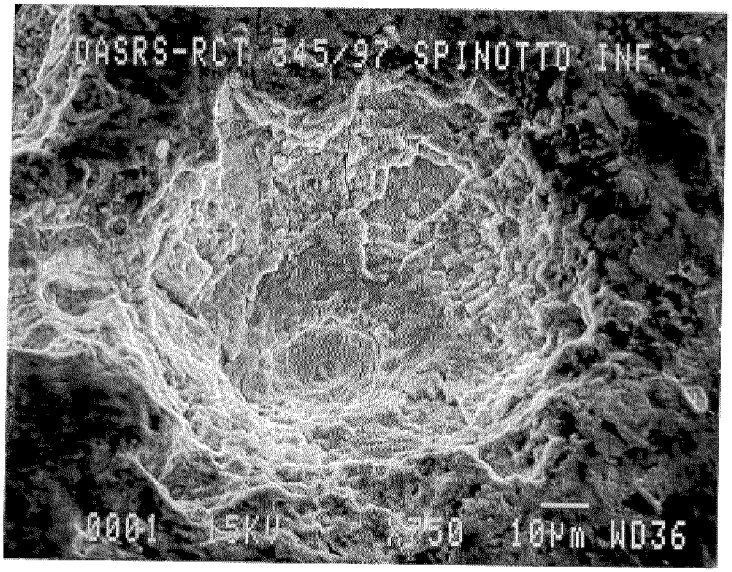

Fig. 14 – Fretting Corrosion on the MB.339 Landing Gear spine

6. CONCLUSIONS

This lecture has given a compendium of the deterioration phenomena induced by corrosion most frequently observed on airframes.

The scheme followed in the presentation of the corrosion forms was derived from the Structural-Electrochemical theory, in order to clarify some aspects common to different corrosion mechanisms.

An always increasing knowledge of the corrosion problems, based on the past experiences and on a multidisciplinary approach comprehensive of design philosophy, condition based maintenance and NDE development, is then essential to win the new economic and safety challenges offered by the aging concerns.

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[4] W. Wallace, D.W. Hoeppner "*AGARD Corrosion Handbook Vol. I – Aircraft Corrosion: Causes and Case Histories*" – AGARDograph N° 278, (July 1985), 79.

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[7] R.D. Mc Cright, "*Effect of Environmental Species and Metallurgical Structure on the Hydrogen Entry into Steel*" – Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys, NACE Pubbl., (June 1973), 306.

[8] R.W. Stahele, M.G. Fontana "*Advances in Corrosion Science and Technology*" – Vol. 7, Plenum Press (New York, 1980), 53-175.