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Advances in Protective Coatings and their Application to Ageing Aircraft

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Abstract

Significant improvements have been achieved in the performance of coatings used in the corrosion protection of military and civil aircraft during the last thirty years. Research into aircraft paints, for example, has resulted in coatings with increased adhesion, fluid resistance and greater flexibility. New methods of paint stripping and novel processes for the repair of pre-treatments and metal coatings are being developed which will lead to reductions in the cost of corrosion maintenance and improved levels of protection. The paper reviews recent developments in aerospace coatings and considers their application in ameliorating some of the corrosion problems associated with ageing aircraft.

1 INTRODUCTION

Advances in aircraft coatings over the last 50 years or so have been in the main part concerned with improving the level of corrosion protection afforded to aerospace components and structures. This has become more critical with the introduction of materials with increased strength and damage tolerance which generally have reduced resistance to corrosion attack. The protection of aluminium parts, for example, has progressed from the use of etch primers over-coated with alkyd and cellulose nitrate/alkyd based paints to schemes involving the use of a pre-treatment, a primer containing a leachable corrosion inhibitor and a polyurethane topcoat [1].

Many of the processes employed in the surface finishing of aerospace parts involve both the use of toxic materials which can be absorbed into the food chain and the use of solvents which can cause damage to the ozone layer and promote smog formation. The protection of aluminium alloys for example is very dependent on the use of chromate-based pre-treatments and chromate pigmented primers. As a result there is increased pressure on the aircraft constructors and operators to adopt environmentally compliant coatings.

This paper first examines the general principles involved in the corrosion protection of aircraft and looks at several examples of in-service corrosion. These have been used to show how the breakdown or failure of protective treatments has led to the initiation of corrosion. The paper reviews the developments in protective treatments and repair methods, which have taken place, and considers how they have been applied to ageing aircraft. Finally new developments in coating technology are discussed and their likely impact on the protection of ageing aircraft is discussed.

2 CORROSION PROTECTION

The protection of both civil and military aircraft is based on reducing the risk of corrosion through design, the selection of materials that are resistant to corrosion and the application of protective treatments to individual components.

2.1 Design

A number of factors need to be considered during the design stage of an aircraft to reduce the risk of corrosion. Some of these are listed in table 1.

Table 1 Corrosion control through design

Potential problem	Design solutions
crevices	use of sealants wet assembly
dissimilar metal contacts	wet assembly metal coatings to reduce differences in galvanic potential shims
water traps	drain holes, fillers
leakage from galleys, toilets	drain paths use of non-metals sealed floor coverings

In some instances, problems experienced on military aircraft have arisen because insufficient consideration has been given to corrosion control through design. The failure on the assembly of components to fill crevices and avoid direct contact between dissimilar metals has often led to the early initiation of corrosion.

2.2 Materials selection

Aluminium alloys easily represent the bulk of the materials used in the construction of ageing aircraft. In many cases high strength aluminium-zinc-magnesium alloys were employed in plate, forging and extrusion product forms in the manufacture of top wing skin panels and landing gear components. Many examples of the 7075 aluminium alloy in the T6 temper can be found on military aircraft presently in service. Similarly 2024 aluminium - copper alloy in the naturally aged T3 temper has been widely used for the construction of lower wing skin panels and fuselage components where good resistance to fatigue cracking is the main requirement. In terms of materials selection for corrosion resistance, 2024-

T351 and 7075-T651 in the form of plate or other thick section forms are poor choices since both alloys are susceptible to exfoliation corrosion and stress corrosion cracking. Unfortunately this was not evident until aircraft built with these materials had been in service for some years.

In the case of the 7075-T651 plate alloy attempts were made to modify the heat treatment to improve the corrosion resistance whilst accepting some reduction in strength. Duplex ageing treatments were introduced which gave lower susceptibility to exfoliation corrosion and stress corrosion cracking. Table 1 compares various tempers of the 7075 alloy.

Table 2 Corrosion behaviour of some 7000 series alloys

Alloy	Temper	Resistance to stress corrosion cracking	Resistance to exfoliation corrosion
7075	T651	D	D
7075	T7351	A	A
7010	T7651	B	B
7010	T73651	A	A/B
7050	T7651	B	B
7050	T73651	A	A/B

A further development was the production of new aluminium - zinc - magnesium alloys 7010 and 7050 which could be heat treated to the T7651 and T73651 tempers to give resistance to exfoliation corrosion and stress corrosion cracking and strength levels comparable to 7075 in the T651 peak aged condition.

Whilst the use of alloys such as 7075 in the T6 condition should be avoided on future aircraft, the replacement of components on existing aircraft with less corrosion susceptible alloys is generally not an option which has been taken. The approach adopted has been to carry out careful audits of the materials used on various ageing aircraft in order to identify areas which may be particularly prone to corrosion attack. This has been complemented with teardowns of aircraft to look for evidence of corrosion in critical areas. Section 3 gives some examples of in-service corrosion problems. The control of corrosion on parts and areas constructed using susceptible materials has been largely through the use of coatings and surface treatments.

2.3 Protective treatments

The standard protective treatments applied to aerospace components are summarised in table 3.

Table 3 Standard protective treatments for aerospace components

Material	Protective treatments
Aluminium alloys	pre-treatment + chromate pigmented primer
Steels	cadmium plating + passivation
Magnesium alloys	pre-treatment + resin + primer
Titanium alloys	anodising

The main protection applied to aluminium alloys is epoxy primer paint pigmented with strontium chromate corrosion inhibitor. This is applied to the aluminium alloy component, which is pre-treated either by anodising in chromic acid, or by applying a chromate conversion coating. The pre-treatment promotes adhesion of the paint to substrate and additionally provides some measure of corrosion protection.

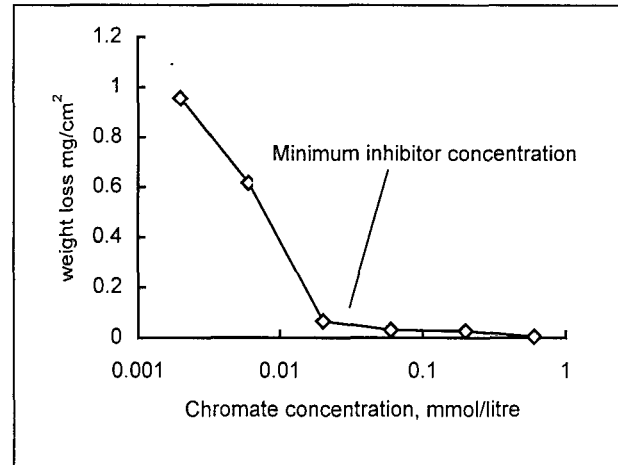


Fig 1. Effect of strontium chromate concentration on the corrosion of 2014-T6 aluminium alloy in 600mM/litre sodium chloride solution

Chromates are very efficient corrosion inhibitors for aluminium alloys particularly in the presence of chloride ions. This is illustrated in fig.1, which shows the effect of strontium chromate concentration on the corrosion of 2014-T4 sheet aluminium alloy in 600mM/litre sodium chloride solution [2]. The data show that provided the concentration is greater than 0.02mM/litre the corrosion attack is prevented. The protection of aluminium alloys by inhibited primers depends on the release of chromate when there is contact with moisture. Chromate based primers currently applied to military aircraft have leaching rates, which ensure that the level of chromate level is well in excess of the critical level given in fig.1. Corrosion is prevented at areas where the paint has become damaged or there is loss of adhesion between the paint and the substrate. Studies made some years ago by Kohler and Scott[3] indicated that chromate levels present in bilge fluid samples were normally well above the critical level indicated in fig.1 to inhibit corrosion.

The preferred scheme for the protection of steel components and fasteners is cadmium plating deposited either by electro-deposition or physical vapour deposition. The cadmium plating acts both as a barrier coating, separating the steel substrate from the environment, and as a sacrificial coating which is able to give protection when the coating becomes damaged. A chromate passivation treatment is applied to the cadmium plating to promote paint adhesion and to improve the corrosion resistance of the coating.

The corrosion protection of magnesium alloys is achieved by applying a barrier coating. The current trend is away from the use of magnesium alloys on aircraft mainly because of its poor corrosion resistance. However many of the ageing military aircraft in service have employed magnesium alloy castings

for gearbox housings, undercarriage components and canopy structures. Magnesium alloy sheet has also been employed for skinning on helicopters and on the rear fuselages of fixed wing aircraft. Severe galvanic corrosion problems arising from cracking of the protective coating around fasteners resulted in major repair programmes with the replacement of magnesium sheet with aluminium alloy sheet. Current design documentation prohibits the use of magnesium alloy sheet on UK military aircraft.

Titanium alloys are generally resistant to corrosion when exposed to aircraft fluids and marine environments. Apart from cleaning they require no further treatment although components are often painted. The normal practice would be to pre-treat by wet abrasive cleaning, etch priming, pickling or anodising and then paint with an epoxy primer. When titanium alloy parts are in contact with components machined from magnesium alloys or aluminium alloys coatings are applied to reduce the risk of galvanic corrosion. Zinc based and aluminium based coatings are frequently employed for this purpose. Coatings are also applied to titanium alloy parts to improve their wear and fretting resistance.

3 IN-SERVICE CORROSION

The various types of corrosion found on fixed wing aircraft and helicopters have been well documented in the AGARD corrosion handbook [4]. A few examples are given below of some of the more common corrosion problems that have been observed by the authors on ageing transport aircraft and fast jets.

These include: -

1. corrosion problems associated with materials selection i.e. use of materials which are inherently susceptible to various forms of attack such as intergranular corrosion, exfoliation corrosion and stress corrosion cracking
2. Problems arising from poor design considerations - e.g. crevice corrosion and dissimilar metal corrosion.

Exfoliation corrosion has been found on the lower wing skins of several military aircraft types currently in service in the United Kingdom. The problem has arisen with panels machined from 2024-T351 plate material. This material has a poor resistance to intergranular and exfoliation corrosion but was originally selected for lower wing skin applications because of its excellent fatigue properties. In each instance breakdown of the protective treatments applied when the aircraft was built, has allowed the metal substrate to become exposed to the environment. Two examples of exfoliation corrosion occurring in-service are described below.

In the first example, extensive exfoliation corrosion was found to have taken place on the internal surfaces of the lower wing skin of a transport aircraft. The main cause of the problem was the leakage of hydraulic fluid. This had degraded the protective scheme, effectively acting as a paint remover. The aircraft was operated in a marine environment and the build up of moisture and led to the initiation of intergranular attack eventually leading to the development of exfoliation corrosion. The protective treatment which had been applied when the aircraft was first built consisted of chromic acid anodising, a prime coat of etch primer and an epoxy top coat pigmented with aluminium. During subsequent repair, the

protective scheme was over-painted with a gloss polyurethane finish to give improved resistance to hydraulic fluids.

In the second example, exfoliation corrosion was found to have developed on the external wing surfaces of a fast jet at areas adjacent to fasteners. The attack initiated in the countersinks and spread parallel to the wing surface. Two factors were believed to play an important role in the initiation of corrosion. The first was the absence of sealant between the fastener and countersink and the second was the cracking of the polyurethane finish. As a result a crevice existed in the fastener \ countersink area permitting the ingress of moisture and the development of exfoliation corrosion. Subsequent repairs involved the blending out of corrosion damage and re-protection using coatings with improved flexibility to reduce the risk of cracking.

Many of the instances of stress corrosion cracking (SCC) found on ageing aircraft occur in parts machined from thick section 7000 series alloys heat-treated to the T6 peak aged condition. Examples of SCC found recently on UK military aircraft include: -

1. SCC in main spars manufactured from material equivalent to 7075-T6. Crack initiation was associated with deterioration of the protective scheme around fasteners
2. SCC in extrusions used for front and rear spar booms made from 7000 series alloys
3. SCC in undercarriage components machined from 7000 series alloy forgings

An example of galvanic or dissimilar metal corrosion was identified on flap shroud panels manufactured from 2024-T351 aluminium alloy. At areas where titanium alloy flap tracks were fastened to the flap shroud panel there was enhanced corrosion attack as result of dissimilar metal contact. The problem was thought to be associated with the absence of wet assembly compound between the titanium track and aluminium alloy flap shroud.

An example of crevice corrosion was found on a leading edge slat that had been manufactured from a clad 2014-T6 aluminium alloy. A modification had been carried out using a stainless steel stiffener, which was adhesively bonded to the slat to improve its fatigue performance. Extensive corrosion was found to have taken place on the clad aluminium alloy skin where it was covered by the stainless steel stiffener. The attack was intergranular in nature and in places penetrated to a depth of 50% of the skin. The stainless steel stiffener had been cadmium plated to reduce the risk of dissimilar metal corrosion with the aluminium alloy skin. Examination of the contacting surfaces indicated that there was only a patchy layer of sealant or adhesive present. It was concluded that corrosion had initiated as a result of the adhesive bond breakdown. The establishment of a crevice would further lead to accelerated corrosion of the aluminium alloy slat.

Invariably problems have arisen with materials, which are inherently susceptible to corrosion as discussed in section 2.2. The cause is associated with a breakdown of the protective scheme, which has been applied. Internal schemes for example are applied when the aircraft is constructed and are generally expected to last the life of the aircraft. Apart from

the application of a supplementary protective scheme to enhance the existing protective treatment, there is usually little opportunity to change or improve the internal protection.

4 RECENT DEVELOPMENTS IN PROTECTIVE COATINGS

4.1 Etch primers

One of the early paint schemes applied to military aircraft was an etch primer, top coated with an epoxy finish. This scheme has not been employed for a number of years and etch primers now only find applications as pre-treatments over which is applied a standard epoxy primer. One of the main developments has been the formulation of etch primers which give enhanced filiform corrosion resistance. BS 2X32 [5] is the current UK standard for etch primers and includes a filiform corrosion test.

A recent application of etch primers has been in the re-protection of the air intake of an aircraft following paint stripping and removal of the corrosion damage. An etch primer was chosen as the pre-treatment rather than the normal chromate conversion coating. The choice was made to avoid the need to deoxidise the surface and water rinse the intake before and after the application of the conversion coating. There was concern that aggressive solutions could have been washed into the internal structure of the aircraft.

4.2 Paints

4.2.1 Epoxy primers

For a number of years, chromate pigmented epoxy primers specified for use on UK military aircraft were qualified to MoD specification DTD 5567 [6]. Developments in the mid 1980s were concerned with improving the adhesion and fluid resistance of the standard primer. This was in response to corrosion problems occurring on civil transport aircraft. Leakage of hydraulic fluids led to degradation of the standard protective coatings and the eventual corrosion attack of the underlying aluminium alloy substrate. New generation primers were developed by the leading aircraft manufacturers, which in addition to giving improved resistance to aircraft fluids also gave greater adhesion.

The current UK aerospace specification for two component epoxy primers is BS 2X33[7] and covers two material types. Type A materials are intended for application to chemically pre-treated substrates suitable for general applications and are equivalent to materials qualified to DTD5567. Type B materials have improved tolerance to the standard of surface preparation and increased chemical resistance. This is reflected in differences in the condition of the substrates used in the qualification tests for paint adhesion. For type A materials, cross hatch adhesion measurements are conducted on aluminium alloy panels (BS L163) which have been acid chromate pickled prior to priming. For type B materials on the other hand measurements are carried out on detergent degreased panels. In each case the pass requirement is the same. For resistance to hydraulic fluid tests the pass criteria is more severe for the type B materials. For example after immersion in tri-*n*-butylphosphate, the load applied in the scratch test for type B materials is 2000g compared with 1000g for type A materials.

For most applications on military aircraft the type B materials are now used.

4.2.2 Acrylic finishes

Acrylic finishes have been used on military aircraft in the United Kingdom over a number of years. They were introduced in the 1970s partly to fulfil a requirement for a paint finish, which could be more readily removed than polyurethane coatings. The UK MoD specification DTD5599 [8] covers this finish. Hoey [9] has indicated that the useful life of an acrylic finish is 2-3 years compared with 5 years for a polyurethane finish. For some time the trend has been away from acrylic finishes and polyurethane schemes with their higher resistance to fluids are now preferred. A further disadvantage of acrylic finishes is their relatively poor resistance to chemical agents. Most fixed wing aircraft are finished in polyurethane schemes and helicopters are being finished in polyurethane schemes when they are repainted.

4.2.3 Polyurethane finishes

Polyurethane finishes have been available for aerospace applications for a number of years. The MoD specification DTD5580 [10] describes the original scheme applied to UK military aircraft. As highlighted earlier in this paper (section 3) one of the main sources of corrosion initiation has been identified as cracking of the paint film around fasteners. One of the main developments in polyurethane finishes has been the formulation of paints, which give coatings with increased tolerance to flexing, a particular problem with large aircraft and helicopters. The current specification for polyurethane finishes is BS 2X34[11]. The specification covers two types of materials type A and type B. Type A materials are intended for interior and exterior use where maximum resistance to fluid attack is required whilst type B materials are intended for exterior surfaces, and offer increased tolerance to flexing compared with type A materials.

4.2.4 Selectively removable paint schemes

The removal of paint from the exterior surface of an aircraft is manpower intensive and involves the handling and disposal of hazardous materials. One approach has been to develop a selectively removable paint scheme which permits the polyurethane top coat to be removed leaving the primer intact. The scheme uses an intermediate coat, typically 8-12 μ m thick, which is applied over a standard epoxy primer. This is then top coated with a polyurethane finish. Blackford [12] has described the use of such schemes on Concorde and Airbus A320 aircraft. Trials have been conducted demonstrating that the polyurethane finish may be removed used a comparatively simple paint stripper.

The recently issued specification BS X35[13] describes the requirements for a selectively removable intermediate coating for aerospace purposes. Two types of intermediate coating are specified. Type A intermediate coating is intended to function with a finish conforming to type A of BS X34 where maximum resistance to fluid attack is required. Type B intermediate coating is intended to function with a finish conforming to type B of BS X34 offering increased tolerance to flexing compared with type A finish. A specification covering the paint remover (BS X36 [14]) has also been issued. A composition for a reference paint remover based on benzyl alcohol is given which meets new VOC requirements.

4.2.5 Low VOC materials

Legislation concerning the release of solvents into the atmosphere was introduced under the 1990 environmental protection act. One area to have an impact on the aerospace industry was on the permitted level of volatile organic compounds in aircraft paints. The current limits are summarised in table 4 and are based on figures given in reference 15.

Table 4 Volatile organic compound emission concentration limits

Coating	VOC emission concentration limits g/litre
Pre-treatment primer	780
Primers	350
Selectively removable intermediate coats	780
Paint removers	300
Top coats	420

The present policy is to procure materials which meet the VOC levels given in table 4 whilst complying to the performance requirements given in the appropriate paint specification. For example the epoxy primer currently being applied to military aircraft is a high solids material. It meets the requirements of BS 2X33 and has a VOC level of less than 350g/litre. This compares with a VOC level of 600 g/litre in the original primers. At present only gloss finishes are available which meet the VOC requirement in table 4. Matt finishes which are used on most military aircraft are still under review.

4.3 Elastomeric coatings

A number of corrosion problems arising on ageing aircraft are related to the cracking of the protective finish around fasteners and the subsequent ingress of moisture. For this reason the BS X34 type B topcoat with greater flexing properties is preferred to the type A finish. For some areas however this finish alone does not provide adequate protection and schemes using elastomeric coatings have been employed. These coatings are self-curing polysulphide based systems which are either applied directly as a primer or are used over a conventional epoxy primer. They have been employed both in the repair of corrosion damage on exterior surfaces and in interior areas where moisture collects and conventional schemes cannot be applied. An example of the latter was in the re-protection of an area housing a fuel bag tank. Moisture collected under the tank causing breakdown of the protective treatment and the eventual development of corrosion. After blending out any corrosion present the surface was re-protected using an etch primer and a polysulphide coating.

One disadvantage of the elastomeric coatings is their thickness. Typically they are applied at a thickness of between 150 to 250µm giving coating weights of around 8oz/sq yard compared with 2oz/sq yard for conventional paint films. Their use has been limited to exterior areas on upper and lower wing skins where corrosion has occurred adjacent to fasteners. One scheme used has replaced the standard epoxy primer with a polysulphide coating which is then over-coated with a flexible polyurethane coating. A second approach has been to apply

the elastomeric coating over a conventional epoxy primer but to restrict it to fastener runs. The surface is then topcoated with a flexible polyurethane finish. Cracking can still occur however due to the mismatch of flexing properties between the different coats. The aim is to improve the corrosion protection at fasteners and minimise the weight penalty.

4.4 Metal coatings

Three areas of coating development have made a significant impact on the corrosion protection of military and civil aircraft. The initial thrust has been in the development of replacement coatings for cadmium and chromium plating but several applications have been identified where they have been used to achieve improved corrosion protection. Developments in electrodeposited zinc alloy coatings, aluminium coatings and metallic-ceramic coatings are discussed below.

4.4.1 Electrodeposited zinc alloy coatings

Electrodeposited zinc alloy coatings have been considered as alternatives to cadmium plating for the protection of steel parts and fasteners. The main interest has been in electrodeposited zinc-nickel and zinc cobalt coatings.

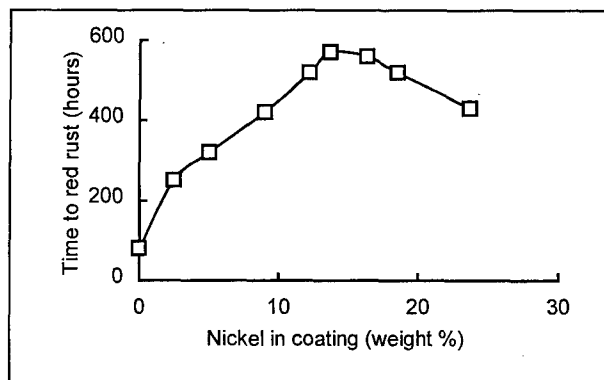


Fig. 2 Effect of nickel concentration on time to first rust on exposure to neutral salt fog

The addition of nickel to zinc coatings greatly improves the corrosion resistance on exposure to neutral salt fog. Fig.2 shows the effect of nickel concentration on the time to first rust [16]. The optimum composition is achieved at ~14% nickel which represents the balance between the barrier and sacrificial properties of the coatings.

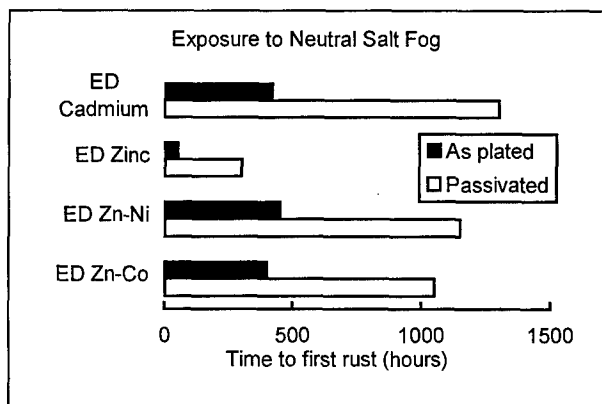


Fig.3 Corrosion behaviour of steel panels with 8µm thick coatings.

Both acid and alkaline zinc - nickel plating baths are available commercially and have been examined as possible alternatives to cadmium plating.

Fig.3 compares the corrosion of several zinc alloy coatings exposed to neutral salt fog [17]. The results obtained show that under these conditions levels of corrosion protection similar to cadmium may be achieved. Currently some aerospace parts manufactured from medium strength steels are being electroplated with zinc alloy coatings.

4.4.2 Aluminium coatings

Aluminium coatings prepared by physical vapour deposition have been generally available in the aerospace industry for more than 20 years. Their applications include the protection of steel parts and fasteners as an alternative to cadmium plating and the plating of titanium alloy fasteners to prevent dissimilar metal corrosion in contact with aluminium alloys. Within the UK PVD aluminium coatings have found comparatively applications on military aircraft. One area where these coatings have been considered is in the protection of parts manufactured from 7075-T651 aluminium alloy where stress corrosion cracking is a concern. Initial laboratory studies [18] have indicated that PVD aluminium coatings may help in delaying the initiation of stress corrosion cracking.

4.4.3 Metallic-ceramic coatings

A variety of commercial coatings are currently available which may be described generically as metallic - ceramic coatings. These consist of an inorganic matrix containing a dispersion of metal flakes or powders. For corrosion protection purposes the most interesting systems are those that are zinc or aluminium based. The coatings have been considered as cadmium replacements however to date their use for this purpose has been fairly limited. Mosser [19] has described the use of aluminium-ceramic coatings as alternatives to cadmium plating for some undercarriage applications.

5 IMPROVED REPAIR SCHEMES

A recent estimate made for the RAF Tornado fleet indicate that on average 296h are spent on each aircraft annually on the removal of corrosion and repair of the protective schemes and equates to an annual cost of around £2M [20]. Calculations have shown that even a modest reduction in corrosion arisings could have a significant impact on aircraft availability. For instance if the number of corrosion arising should be reduced by 10%, the time spent by the Tornado fleet on 3rd line maintenance would be reduced by 56 days. Aircraft availability can be further improved by introducing more effective methods of repair, which reduce the time spent on repair and give improved protection. Three areas are considered below, paint removal, corrosion removal and the use of brush plating and anodising techniques.

5.1 Paint removal

The paint schemes applied to the external surfaces of aircraft generally have a service life of between 4 and 5 years. The normal practice has been to remove all the protective treatment from the aircraft surface using a chemical paint stripper to expose the metal substrate. This allows inspection of the airframe for evidence of corrosion attack and fatigue cracking.

Most military aircraft are finished with a polyurethane topcoat selected because of its high resistance to fluids. The only chemical paint strippers, which are effective on these types of coating, are based on methylene chloride with additives of phenol. These are unpleasant and hazardous to use and much effort has been directed towards finding more effective and safer methods of paint removal.

Plastic media stripping (PMS) has become an important method of removing paint from military aircraft. The process involves the impacting of small plastic beads onto the painted surface. The equipment developed allows the plastic beads to be blasted at the work surface at a controlled velocity and to recycle spent beads removing dust and paint particles. Facilities have been installed allowing small components to be stripped as well as complete aircraft. There are still some concerns regarding the treatment of thin sheet, clad alloys and composite materials. Other blasting media such as dry ice, and wheat starch have been evaluated. There is also interest in laser techniques, possibly for use at areas around fasteners.

5.2 Corrosion removal

Impact blasting techniques such as shot peening and abrasive blast cleaning are widely used in the aerospace industry for the preparation of metal surfaces. In shot peening operations, the workpiece is blasted with a high velocity stream of spherical particles such as glass balls or steel shot in order to induce compressive stresses into the surface. The process is mainly used to improve the fatigue strength of components and to give improved resistance to stress corrosion cracking. Abrasive blast cleaning is used to remove corrosion products or scale from metal components or to roughen the surface in preparation for bonding, painting or metal coating. The abrasives which are employed include alumina grit, angular metallic particles, crushed slag and smooth glass beads.

In recent years abrasive blast cleaning with either small diameter glass beads or fine alumina grit has been used to blend out corrosion damage on aircraft. One area where it has proved to be invaluable has been in the repair of corrosion damage that sometimes occurs adjacent to countersink fasteners, particularly on upper wing skins. Prior to the introduction of abrasive blast cleaning, the corrosion was blended out by hand using metal wool, abrasive pads or small abrasive wheels mounted in a power drill. This could take up to 2 hours for a single fastener head but by using abrasive blasting techniques this time has been reduced to a few minutes.

When abrasive blast cleaning methods were first introduced for use on military aircraft, glass beads were preferred to alumina grit because they readily remove brittle corrosion products but remove little of the ductile metal substrate. It became apparent, however, that although the surface appeared free of corrosion after blasting the peening action of the glass beads could deform the surface layers and cause small pockets of corrosion in pits or intergranular sites to become trapped. There was concern that these pockets of buried corrosion might act as stress concentrators which could accelerate fatigue crack initiation or allow enhanced corrosion attack. A change to alumina grit blasting was therefore made in order to ensure that all the corrosion was blended out even though this would lead to a significant amount of metal removal.

Research conducted at DERA by Smith and Hewins [21] examined the effects of abrasive blast cleaning on the fatigue of a 2014-T6 aluminium alloy. Table 5 compares the fatigue strength at 10^7 cycles determined using rotating bending tests. The results indicate that although there is a significant loss in fatigue strength following exposure to neutral salt fog this can largely be restored by abrasive blasting.

Table 5 Fatigue strength (M Pa) at 10^7 cycles

	None	8h exposure to neutral salt fog
As machined	170	107
Alumina grit blasted	165	150
Glass bead blasted	175	160

Alumina grit blasting is now extensively used in the blending out of corrosion damage.

5.3 Brush plating

Brush plating techniques allow the in-situ repair of metal coatings on aircraft. The main application has been on the repair of damaged cadmium plating on landing gear components. Research undertaken at DERA has explored the use of brush plated zinc alloy coatings for the repair of corroded metal coatings [22]. Trials were conducted on a commercial zinc-nickel coating and on two experimental coatings, a zinc-nickel and a zinc-cobalt. In neutral salt fog tests, encouraging results were obtained with the experimental zinc-cobalt system. A series of experiments were conducted using steel test panels which had been plated with electrodeposited cadmium, PVD aluminium, electrodeposited zinc-nickel or electrodeposited zinc-cobalt coatings. The panels were then damaged by removing the centre portion of the coating. The bare steel was then repaired by brush plating. Corrosion tests indicated that brush plated zinc - nickel and zinc - cobalt coatings could be used to repair a range of coatings including bath plated zinc-nickel, zinc-cobalt, PVD aluminium and bath plated cadmium. Further details of the research programme are given in reference 22.

5.4 Brush anodising

Recent research at DERA has examined the use of brush anodising techniques for the repair of protective treatments [23]. Trials were conducted on two sheet aluminium alloys, an aluminium copper alloy 2014-T6 and an aluminium - zinc - magnesium alloy 7075-T6. Three commercial brush anodising treatments were evaluated, a sulphuric acid solution, a boric-sulphuric acid solution and a chromic acid control. Corrosion tests were made on samples, which had been bath anodised and then damaged and repaired using brush anodising. The results obtained showed that satisfactory repairs could be made using the boric-sulphuric acid brush anodising process. The work is at an early stage and further research is needed to develop a practical repair process.

6 FUTURE COATING DEVELOPMENTS

Many of the developments in coating technology for aerospace applications are being driven by the need to replace existing protective treatments with environmentally compliant systems.

Trials have been conducted at DERA on a number of commercial chromate-free primers [24]. Accelerated and marine exposure trials have shown that these coatings do not produce the same level of protection as the standard chromate pigmented epoxy primers currently in-service. Under laboratory tests, the chromate-free systems failed to give protection to the substrate at areas where the paint scheme was damaged. This was also observed in marine exposure trials and additionally evidence of filiform corrosion was found after 2 years with a number of the schemes. It was concluded that the most promising materials could have applications on the exterior surfaces of civil aircraft operating in a relatively benign environment but were unsuitable for use on military aircraft.

Research is currently in progress within Europe to develop new surface cleaning and etching processes, which reduce the use of solvents and chromates. Replacements for chromate based anodising processes and conversion coatings are also being investigated and attempts are being made to develop chromate-free primers and sealants. The eventual aim is to introduce a chromate-free protection scheme that will be used both in the manufacture of new aircraft and in the maintenance and repair of aircraft in service.

The last 30 years has seen the development of advanced tape technologies for aerospace applications. This has included protection against erosion, corrosion, abrasion and impact damage. One area currently being evaluated is the use of appliqué technology for the replacement of aircraft topcoats. This could have a major impact on the protection and maintenance of ageing aircraft by reducing the requirement for extensive painting and paint removal facilities and increasing aircraft availability.

In the field of metal coatings, some of the major advances relevant to aerospace have been in the field of PVD coatings. Coatings under development include:-

- aluminium alloy coatings to replace cadmium plating on steel components [25]
- multilayered coatings for fasteners and parts where combinations of corrosion and wear resistance are needed

Although initially intended for new aircraft it is likely that these coatings will ultimately find applications on ageing aircraft to improve corrosion protection.

7 CONCLUSIONS

The protection of military aircraft against corrosion is based on the selection of corrosion resistant materials, the application of protective treatments and careful design to avoid potential corrosion problems such as crevices, dissimilar metal contacts and water traps. One of the main problems associated with ageing aircraft is the extensive use of structural materials that are inherently susceptible to corrosion. In many instances the protective treatments applied when the aircraft was built have proved inadequate and poor design against corrosion has resulted in many corrosion arising. Although there have been advances in aluminium alloy technology with the development of new tempers and

compositions which combine good mechanical properties with high corrosion resistance, material substitution is generally not an option. Instead the approach has been to look for more effective repair methods and coatings. In general developments in coatings have been incremental rather than major leaps forward. Paints with increased fluid resistance, flexibility and adhesion are replacing existing schemes. An added problem facing the maintenance and repair of ageing aircraft is environmental legislation. This is having a major impact on the aerospace industry to the effect that many of the current protective schemes will not be available in the future.

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