



CORROSION RESISTANCE OF ALUMINIUM - POCKET GUIDE

AND PROTECTIVE MEASURES WHERE APPROPRIATE



ABSTRACT

Aluminium and its alloys have excellent resistance to corrosion. It does corrode under some conditions. It is preferable to avoid corrosion through appropriate alloy choice and geometric design.

Corrosion is a function of the operating environment, alloy and design. Understanding the mechanisms of corrosion enables more appropriate choices of alloy, geometry and detail in design and fabrication.

To obtain the good results that are possible with aluminium, it is essential to know the conditions under which corrosion can occur:

- The form the corrosion can take
- The rate or severity of attack
- The preventative measures that can be taken to avoid corrosion by design choices and to prevent premature failure through appropriate prevention detail

This Pocket Guide provides some information on practical corrosion problems that may arise when using aluminium. It discusses appropriate preventative measures to eliminate or inhibit corrosion.

1. INTRODUCTION TO CORROSION

What is corrosion?

Corrosion is a natural process as nature attempts to return metals to their original, stable, oxidised state. The degree and

severity of corrosion is a function of both the material and its operating environment.

Aluminium has a very high affinity with oxygen. Only Beryllium has a higher affinity. When a new aluminium surface is exposed in the presence of air (or an oxidising agent), it very rapidly acquires a thin, compact, hard, tightly adhering, protective, self healing film of aluminium oxide (about $0,5\mu$ in air). In non-stagnant water, thicker films (of hydrated oxide) are produced. This film is relatively inert chemically. It is on the inactivity of the surface film that the good corrosion resistance of aluminium depends. When the surface film dissolves, dissolution of the metal (corrosion) occurs; when the film suffers localised damage under conditions when self-healing cannot occur, localised corrosion follows. This may take the form of pitting corrosion, crevice corrosion, inter-

granular corrosion or stress corrosion, depending on the circumstances involved. The formation of the oxide is illustrated in Figure 1, and a comparison of the oxide characteristics in Figure 2.

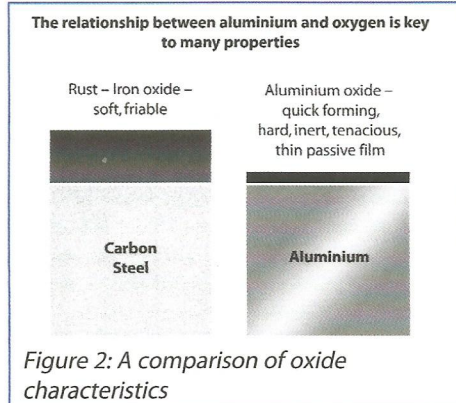
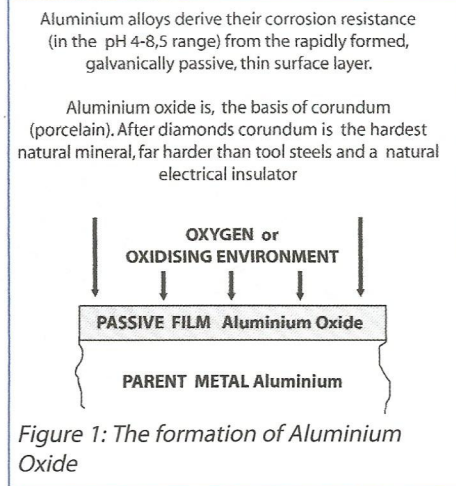
Exposed to oxygen or to an oxidising environment, aluminium and its alloys have excellent resistance to corrosion. Many of its uses depend on this very property.

The surface films are generally stable in the pH range of about 4,5 - 8. There are cases beyond this range where the film is inert, e.g., the film is inert in concentrated nitric acid at pH 0, glacial acetic acid at pH 3 and in ammonium hydroxide at pH 13. The oxide film is, however, generally dissolved in most strong acids and bases. Corrosion of aluminium in these is rapid.

Surprisingly, much remains to be learned about the properties and compositions of the oxide surface film on aluminium.

As is the case with all common structural and architectural metals, aluminium does corrode under some conditions. This especially occurs when the wrong alloy is chosen, or it is incorrectly used for the application. To obtain the good results that are possible with aluminium, it is essential to know the conditions under which corrosion can occur, the form the corrosion can take, the rate or severity of the attack and most important of all, the preventative measures that can be taken.

Most corrosive atmospheric environments contain oxides of sulphur that are by-products from the combustion of oil, petrol or coal. Sulphur dioxide, by far the most commonly occurring oxide of sulphur, is absorbed from the atmosphere onto most metallic surfaces. This is particularly so for iron and steel. When conditions are humid, the sulphur dioxide is converted to sulphuric acid, with iron sulphate an intermediate product. In the case of aluminium and other non ferrous metals, this sulphuric acid is absorbed in the corrosion process. It gives rise to the formation of metallic sulphates. However, in iron and steel the sulphuric acid is regenerated as a result of hydrolysis and the corrosion reaction continues.



Because the addition of alloying elements to the aluminium affects its corrosion resistance, it is difficult to make general statements of its corrosion performance. To create some degree of order and perspective in this guide some generalisation must be made.

In general, aluminium alloys have good corrosion resistance in the following environments:

Atmospheres (rural, industrial, marine):

- Fresh Waters (natural, treated, reclaimed)
- Sea Waters (quay side, open water)

They also offer good corrosion resistance to:

- Most soils
- Most foods and
- Many Chemicals

2. CORROSION MECHANISMS

2.1 General Corrosion

The general rate of surface corrosion in local atmospheres was measured in various South African inland and coastal centres in 25 year long term studies by the CSIR. Whilst somewhat more than stainless steels, the general corrosion of aluminium was about 20% that of zinc and 1% that of low carbon steels.

2.2 Pitting Corrosion

Pitting is the most common form of corrosion found in aluminium. Most alloys are affected to varying degrees depending on their composition, thermal history and the environmental conditions. As pitting is a galvanic reaction between elements in the alloy, in general, the purer and simpler the alloy the higher its resistance to pitting. The rate of penetration usually diminishes with time (Figure 3). The pit depth is typically limited to 0,5mm. If the metal gauge is adequate, perforation may not occur for a considerable time. The reason for the slowing reaction is the filling of the pit by hydrated aluminium oxide, a gel like product that occupies +/- 20 times the volume of the

pit. This hydrated oxide can also fill fairly tight crevices in fabricated assemblies reducing their propensity to corrode. As only a small amount of metal is removed, the mechanical properties are not significantly affected. The product of corrosion leaves a white bloom around the pit.

From an engineering point of view, no major protective measures are necessary. However, for building prestige purposes where the initial bright surface finish has to be maintained, the material is usually anodised or organic powder coated. A 6-monthly wash with a mild detergent, followed by thorough rinsing, is usually adequate to maintain the surface.

Although pitting normally diminishes with time in liquid media, the pits do not as readily stifle. Perforation may result. Prior to such an application, it is advisable to assess the corrosivity of the medium under operating conditions to aluminium. This is accomplished by laboratory tests.

Initial protection is always the best defense. The following steps could be employed to prevent premature failure:

- Anodising
- Using alclad aluminium
- Electroplating, e.g. with nickel
- Painting
- Avoiding stagnant conditions as this is contributory to the onset of pitting.
- Avoiding the use of steel, brass or copper fittings in, or in feeds, to liquid storage systems. Copper ions leaching into the storage media cause severe pitting of aluminium.

2.3 Galvanic Corrosion

Galvanic corrosion is a natural reaction between metals (and carbon) in contact in the presence of an electrolyte. (The well known zinc carbon battery is an example of a galvanic reaction in which zinc, the anode, is consumed.) Aluminium is a more active, more anodic, material than most. When aluminium is placed in contact with a more cathodic metal (i.e a metal other than magnesium, zinc or cadmium), in the presence of an electrolyte; it usually tends to corrode more rapidly than it would if exposed to this same environment by itself. The rate is determined by the potential difference between aluminium and the specific metal under consideration (as measured by the Galvanic Series), the ratio of areas, and the characteristics of the electrolyte in the operating environment. Aluminium is also highly anodic to active carbon. Active carbon is found in some gaskets and washers used in building construction. Particularly in very humid or wet areas a limitation of active carbon to 3% is recommended.

This is minimised or prevented in many ways, such as:

- Removing or neutralising the electrolyte
- Choosing metals for construction which

are close together in the galvanic series. This minimises the potential difference, e.g. aluminium brackets cadmium.

- Design so as to obtain a much larger anodic area (corroding metal) than cathodic area. This results in the corrosion current flowing over a larger surface, which reduces the corrosion rate.
- Electrically insulating one metal from the other to prevent flow of current.

An apparent anomaly to galvanic corrosion is the relationship between Austenitic stainless steel and aluminium. Stainless steel is protected by a chromium oxide surface layer. Chrome oxide is passive to the aluminium oxide layer on aluminium.

In addition, hot dip galvanized steel bolts may be used both because the zinc initially protects the aluminium galvanically, and the ratio of the bolt to the substrate is normally low. When the zinc is worn away, a galvanic couple forms between the aluminium and the steel. Coating the contact area has proved successful in avoiding the local pitting corrosion.

Corrosion design related to galvanic interaction needs to accommodate possibilities which could lead to failure. As an example, as bilges of ships are typically fabricated from one alloy they should not react. However, they are also typically damp, if not wet. Because of the possibility of dropping nuts or steel tools into the bilge area during construction or maintenance, protection in the form of coating is recommended.

2.4 Inter-granular corrosion

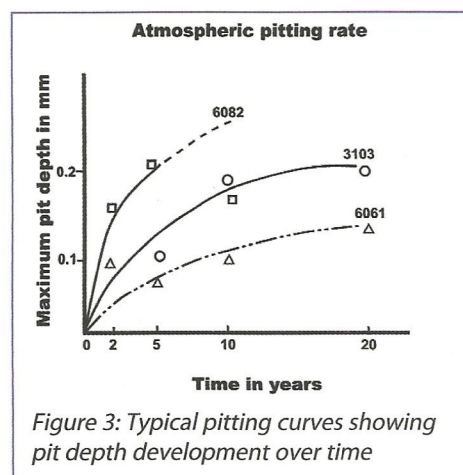
Visually, inter-granular corrosion is less noticeable than pitting or galvanic corrosion since it is confined to the very narrow grain boundary regions of one of the alloying elements. These boundaries are either enriched or depleted. The mechanical properties of the metal are compromised.

It is recommended that:

- MgSi alloys (6xxx series) used for structures should have a minimum section thickness of 1,5 to 2mm for extrusions and 3 to 5 mm for plate, (depending on the severity of the environment.)
- Alloys based on AlCu (Mg) (e.g. 2024) should be protected.
- The medium strength AlZnMg (eg 7017, 7020) alloys should be clad or metal-sprayed in severe environments.
- In AlMg alloys (5xxx series) that contain more than 3-4% Mg, the magnesium tends to precipitate preferentially at the grain boundaries.
- These may become susceptible to corrosion if associated with high rates of strain hardening.

2.5 Exfoliation (lamellae attack)

This is a form of corrosion which propagates



simultaneously along several grain boundaries parallel to the metal surface. The residual metal between the corrosion paths then opens up like the leaves of a book. Because of this, exfoliation corrosion is easily recognized. From a service viewpoint exfoliation corrosion must be regarded as serious, as it leads to reduction in thickness and strength, which could lead to failure.

Experience indicates that specific conditions are required to initiate exfoliation, which probably explains its infrequent occurrence. Large amounts of cold work, either residual from the production process or introduced during fabrication or service, increase susceptibility. For example, cutting alloys in the hard temper condition by shearing will produce regions which exfoliate. Cold stamping of identification marks produces highly worked areas which have a similar effect. Cold forming of AlMg rivet heads has also caused exfoliation with eventual loss of the heads. Hot forming is advised.

The avoidance of shearing of hard materials, cladding, painting and metal spraying are some methods of protection against exfoliation. Susceptibility in the heat treatable alloys can be reduced by over-aging.

2.6 Stress Corrosion

Stress corrosion is regarded as the most serious form of attack since, if not recognised, it can lead to sudden failure of a component. Visually it may be very difficult to see. Its only manifestation may be cracks, there being little or no corrosion product.

From a service point of view, attention need only be paid to the high strength AlZnMgCu aircraft alloys (7xxx series), those based on the AlCu system (eg 2024), the medium strength AlZnMg alloys and the high Magnesium AlMg alloys.

2.7 Poulitce Corrosion

Any absorbent material, (such as paper, asbestos, sawdust, soils and similar materials), which is in contact with aluminium and becomes soggy due to condensation or water entrapment tends to promote stagnant water. Oxygen is occluded. The aluminum may corrode. Good design avoids the use of such materials in contact with aluminium under moist conditions. Porous gasket materials should not be used. Unfortunately as it is normally not possible to predict the likelihood of moist conditions during service, absorbent gaskets are not recommended.

2.8 Crevice Corrosion

This is an anaerobic, localised corrosion in gaps narrower than about 1mm. The meniscus forces of water draw and inhibit drying and the necessary exposure to oxygen. Starting as a result of differential aeration, corrosion occurs at an accelerated rate in the form of

pits and etche at patches within a crevice between the two surfaces.

One of the most common examples of crevice corrosion is water-staining of aluminium sheet and extruded products. A grey to black stained patch develops when water is trapped between adjacent surfaces during storage or transit. Whilst water staining does not reduce the structural properties of the substrate, it is of practical importance where surface appearance is important. Subsequent surface treatment will not hide water staining.

Crevice corrosion can be avoided by:

- Careful design to avoid narrow gaps,
- Application of some protection to the facing surfaces, e.g. sealing with non acid based silicone sealant or coating.
- Avoidance of moist conditions during storage and transportation.
- Allowing the free flow of dry air between sections, sheets or plates.

2.9 Fretting Corrosion

This is a form of erosion caused by materials rubbing against each other (e.g. during transport). A variation of this is when material is cut and the shavings inadequately removed before wrapping.

2.10 Filiform Corrosion

This is an under film corrosion affecting coated surfaces. As powder coating is hygroscopic, continuous exposure to high humidity can result in an attack on the aluminium substrate. In high humidity conditions a two coat system is recommended with the first coat being either anodising or a suitable epoxy coating.

2.11 Bacterial Corrosion

Regarding aluminium, typically this occurs when water is allowed to become stagnant in undrained constructions which never dry. A good example is in handrail supports completely embedded in concrete such that they can neither drain nor facilitate the free flow of oxygen to affected surfaces.

In the presence of oxygen, aerobic bacteria form sulfides resulting in corrosion. Without the presence of oxygen, anaerobic bacteria are common. Layers of anaerobic bacteria can exist in the inner parts of the corrosion deposits, while the outer parts are inhabited by aerobic bacteria.

Bacterial colonies and deposits can form concentration cells, causing and enhancing galvanic corrosion. Bacterial corrosion may also appear in a form of pitting corrosion.

3. OPERATING ENVIRONMENT

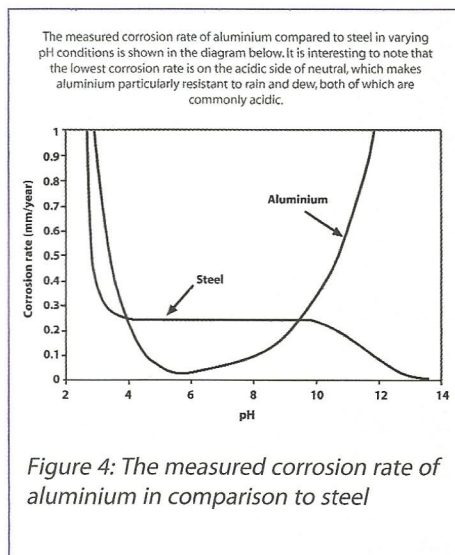
This section is divided into three categories:

- Aluminium exposed to natural atmospheric conditions

- Aluminium exposed to chemicals
- Aluminium in engineering applications

3.1 Aluminium exposed to natural atmospheric conditions

Aluminium structures generally require little or no protection in normal atmospheres. The need is dependent on environmental conditions, particularly in industrial or marine areas and on the alloy used. Surface appearance will vary from the original mill finish in mild environments tending towards



an even grey colour to a rough, grey, stone-like appearance in aggressive coastal and marine environments.

Tables 1 and 2 shows the ISO 9223 categorisation of corrosivity in South Africa. Table 2 shows the recommended anodising and powder coating thicknesses. This also protects surfaces.

3.2 Aluminium exposed to chemicals

Aluminium is generally corrosion resistant in the pH range 4,5 to 8,5. Aluminium is successfully used in association with a wide range of chemicals, foodstuffs and fuels. AFSA has a listing of Aluminium 1xxx, 3xxx and 5xxx series corrosion potential relationships with over 1000 chemicals, foodstuffs and fuels at different temperatures between 0° and 100°C.

3.3.1 Fresh Water

Except in cases of high temperature oxidation and gas metal reactions, which are encountered in specialised industries, there is no corrosion of aluminium unless water is present. Water acts as an electrolyte.

In some cases however, water is beneficial. For example, in aggressive marine and industrial atmospheres, aluminium will last longer if it is rained on frequently as the water will dilute and wash away corrosive salt or soot. In certain organic chemicals, such as phenols, traces of water inhibit corrosion.

Code	Geographic area	ISO 9223 category	Distance from sea/ source of corrosion (km)	Recommended thicknesses Powder coating	Recommended thicknesses Decorative anodising ext/ int
A	Namibia and the North Western Cape shoreline Desert shoreline and coastal fog zone (North of Olifants River)	>C5	<5	60µ - 120µ*	25µ/25µ
B	Western Cape Atlantic shoreline arid shoreline with fog or strong winds (False Bay to Olifants river)	C5	<3	60µ	25µ/25µ
C	Western Cape coastal area (to range of fall out of salt aerosols)	C4	5 to 15	60µ	25µ/15µ
D	Western Cape Urban Coastal/ urban/industrial (and surrounds)	C4/C5	<20	60µ	25µ/25µ
E	South and East Cape shoreline Temperate shoreline (Distance from ocean varies with terrain)	C5	<2	60µ	25µ/25µ
F	South and East Cape coastal Temperate coastline (Distance from ocean varies with terrain)	C4	5 to 10	60µ	25µ/15µ
G	KwaZulu Natal shoreline Subtropical shoreline (KwaZulu Natal to Maputo)	>C5	<3	60µ- 120µ*	25µ/25µ
H	KwaZulu Natal coastal. Subtropical coastal (distance varies with terrain)	C4	10 to 20	60µ	25µ/15µ
I	Durban (urban). Urban and industrial, inland of shoreline - Prospecton to Umhlanga, to Pinetown	C4/C5	10 to 20	60µ	25µ/25µ
J	Richards Bay. Urban and industrial, inland of shoreline	C4/C5	<20	60µ	25µ/25µ
K	Coastal cities, industrial and heavy traffic areas. (Areas of Port Elizabeth, East London and Pinetown)	C5	<10 to 15	60µ	25µ/25µ
L	Highveld general areas. Rural and suburban areas	C3		60µ	15µ/15µ
M	Highveld urban and industrial High traffic urban, or close to heavy industry. East Rand, areas of Pretoria and Witbank	C4		60µ	25µ/25µ
N	Remainder of country	C2 to C3		60µ	15µ/15µ
O	Areas of high sand/wind abrasion			60µ	25µ/25µ

Table 2: Application of ISO 9223 categorisation of corrosivity to South Africa including the recommended anodising and powder coating thicknesses.

* In high humidity or constantly wet areas, additional steps are required to avoid filiform corrosion as powder coatings are hygroscopic. Either unsealed anodising or a self etching epoxy can be applied.

ISO 9223 corrosivity category	C1	C2	C3	C4	C5	>C5
Description	Very Low	Low	Medium	High	Very High	>very high
Area code	-	N	L	C,E,D,F,H,I, J,M	B,D,E,I,J,K	A,G,H

Table 1: ISO 9223 categorisation of corrosivity

3.3.2 Temperature

Most electrolytes are water based. Between 0°C (ice) and 100°C (steam) an increase in temperature has a strong accelerating effect on corrosion of aluminium.

However, in the atmosphere, heat can be beneficial as the surface dries more rapidly. In some locations, power lines which had been shut down corroded faster than the live ones because the beneficial influence of high temperature had been lost. However, in foggy environments, for example, a live cable may remain damp and the effect of higher temperature will accelerate corrosion.

This guide relates to the normal range of daily operating temperatures. Where higher temperatures are encountered, e.g., in heat exchangers, seeking advice is recommended.

3.3.3 Surface to Volume Ratio

The surface to volume ratio of a metal object has a marked influence on its corrosion life. If the ratio is high, the metal deteriorates more rapidly than it does when the ratio is low because more of the substrate is offered for reaction. For equal geometry a smooth surface will deteriorate slower than a rough surface. Less surface area is exposed.

3.3.4 Heat Capacity of the Surface

This effect may be due to the thickness of the metal itself or to the heat capacity of other objects to which the metal is affixed. If an unpainted aluminium-skinned aircraft is poorly maintained; pitting would be seen to be most pronounced on the undersides of the wings. These have a lower rate of heating and cooling and subsequently remain cold (and wet) longer than the rest of the aircraft's skin. They retain condensation for a longer period.

3.3.5 Impurities in the Environment

Aluminium may have proved itself an excellent material for handling a specific chemical. However, later batches of the same chemical may contain impurities which do not affect the commercial quality of the chemical, but may lead to corrosion of the aluminium vessels, e.g. traces of copper from production equipment.

4. ALUMINIUM AND ALUMINIUM ALLOYS

4.1 Influence of Alloying

Commercially pure aluminium (1xxx) has the best corrosion resistance. Performance drops sharply with the introduction of impurities, particularly copper and iron but increases with the introduction of magnesium or zinc. The metallurgical treatment of the alloy markedly influences performance as it determines the structure as well as the scale, state and location of metallic phases.

Alloy Group	Major alloying element	Strength	Ductility	Corrosion resistance	Weldability	Anodising
1xxx	None	L	H	H	H	VH
2xxx	Cu	VH	L	L	L	L
3xxx	Mn	L+	H	H	H	H
5xxx	Mg	M	M	H	H	H
6xxx	Si/Mg	M	M	H	H	VH -H
7xxx	Zn/Mg	H	L	M	M	M
7xxxCu	Zn/Mg/Cu	VH	L	L	L	L

L = Low, M = Medium, H = High, VH = Very High

Table 3: The relative performance relationship between aluminium alloys.

Alloying elements used to achieve desirable properties of most commercial aluminium alloy groups are listed in Table 3. These elements, added in small percentages, are developed to have special market related properties such as strength, ductility, weldability, machinability, corrosion resistance, etc. The alloy groups are typically used in different markets. Whilst the major elemental additions contribution to corrosion is discussed the minor elements and other additions also have effects that could require consideration. Aluminium alloy data sheets give guidance.

In applications where aluminium has been found to be generally satisfactory, the most common complaints have been due to the improper choice of alloy, poor design, faulty construction and unexpected contamination of normally non-aggressive environments.

The main engineering alloy groups are the 5xxx and the 6xxx series, the 2xxx and 7xxx being generally confined to the aero-space sector. The 1xxx series is used for electrical transmission, in packaging, for chemical storage, and as a heat reflective insulation material.

4.2 Important Alloy Groups

4.2.1 Al-Copper Group (2xxx)

The 2xxx series have relatively poor resistance to corrosion and require surface protection when used, especially in marine and industrial atmospheres.

4.2.2 Al-Magnesium Group (5xxx)

In general, AlMg alloys have the best corrosion resistance of all the alloys. However, above about 4% Mg, fabrication practice has a marked influence on long-term corrosion behaviour. Where temperatures are in excess of 60°C and they are highly strain hardened, they may become susceptible to stress or exfoliation corrosion.

The reason for this is that when magnesium is present in quantities greater than about 3-4%, there is a tendency for the AlMg beta-phase to precipitate in the grain boundaries. This leads to inter-granular and stress corrosion in aggressive environments. Marine codes

place limits on Mg at 5.5% and temper at H116, a low degree of strain hardening.

A typical and very important example is the case of AlMg alloy rivets and bolts which fail prematurely due to the stress raisers introduced in the heads during fixing.

4.2.3 Al-Magnesium-Silicon Alloys (6xxx)

These alloys offer the best resistance to corrosion when the silicon percentage does not exceed the amount needed to combine with the magnesium content to form MgSi.

The 6xxx alloys have good general corrosion resistance. The resistance is inferior to the copper-free AlMn alloys (3xxx) and the AlMg alloys (5xxx).

4.2.4 Aluminium-Zinc-Magnesium Alloys (7xxx)

There are three distinct sub-groups in the family:

- AlZn alloys
Containing about 1% Zn and used as sacrificial anodic cladding.
- Medium Strength Alloys
These contain 3 - 5% Zinc and 1- 3%

Alloy	Condition	Form	Durability rating
1050	H14	Sheet	A
3103	H14/H18	Sheet	A
3105	H14/H16/H18	Sheet	A
5083	O/ H22	Sheet and plate	A
5754	O/H22/H24/H26	Sheet and plate	A
5251	O/H22/H24/H26	Sheet and plate	A
5454	H22/H24	Sheet and plate	A
6061	T6	Extrusions	B
6063	T6	Extrusions	B
6082	T6	Extrusions	B
7020	T4/T6	Extrusion	C
LM5 (51000)	Sand/Chill	Casting	A
LM6 (44100)	Sand/Chill	Casting	B
LM25 (42100)	Sand/Chill	Casting	B

Table 4: Durability ratings of some common aluminium alloys

Magnesium. Their main advantage lies in their ability to age harden at room temperature. After welding the alloy regains the strength lost in the heat affect zone. After only a few weeks, very high weld strengths and efficiencies are obtained.

● High Strength Alloys

These are typically aircraft alloys. They require protection in severe environments and might be considered in the same class as the AlZnMgCu alloys. Improper heat treatment can make them susceptible to stress corrosion. In applications where aluminium has been found to be generally satisfactory, the most common complaints have been due to the improper choice of alloy, poor design, faulty construction and unexpected contamination of normally non-aggressive environments.

4.2.5 Aluminium-Zinc-Magnesium-Copper Alloys (7xxx)

Typified by 7075 alloy, these have similar corrosion behaviour to the AlCu group. They also require protection in corrosive environments. Most components manufactured from this alloy are anodised and/or painted to afford some protection from corrosion during service.

4.3 General Alloy Problems

Very sophisticated alloy systems and the present state of technology of the aluminium industry make it possible to choose an appropriate alloy for a specific end use and set of operating circumstances.

Two examples follow:

- AlCu(2xxx series), have unfortunately frequently been chosen for marine purposes. They are stronger, but at the expense of corrosion resistance. The choice is usually in ignorance of

expected results in operation but sometimes through careless alloy identification. Poor alloy choices are unfortunately only recognised after failure.

- Occasionally, an aluminium-copper alloy plate is heated with a blow torch to facilitate bending. Although the bending operation is accomplished easily, the material is made very much more susceptible to exfoliation corrosion.

An AlMg alloy such as 5083 would have sufficed for this application and lasted far better.

4.4 Durability ratings

To formulate rules for the protection of aluminium structures, Table 4 lists durability ratings as established for different alloys available in South Africa. The durability listings are drawn from the British Standard BS 8118:1991 "Structural Use of Aluminium", Tables 2.1 and 2.2. These are the reference durability ratings used in later discussion of metal to metal contacts.

5. APPLICATIONS AND RECOMMENDATIONS

5.1 Protective Measures - Normal atmospheric conditions

Aluminium structures generally require little or no protection in normal atmospheres. The need is really dependent on environmental conditions particularly in industrial or marine areas and the alloy used. Surface appearance will vary from the original mill finish in mild environments tending towards an even grey colour to a rough, grey, stone-like appearance in aggressive coastal and marine environments where protection may become necessary. Table 5 shows the general level of protection required.

When in contact with other metals or substrates, special protection is necessary, especially in the presence of sea-spray or salt splashing. Drainage of water from copper or copper-alloy roofs onto aluminium can result in severe pitting and must be avoided.

Aluminium may require some protection in a normal atmospheric environment. Refer to section 3.1.

5.1.1 Anodising/ Organic coating (Painting)

Anodising and powder coatings are commonly used to decorate architectural surfaces. These finishes, correctly applied, also enhance corrosion resistance. Anodising or powder coating must, however, be preceded by appropriate pre-treatment and the following operations must be performed in sequence, without any delay between them. The AFSA handbook on surface finishes gives detail of recommended film thickness

Procedures according to the environment						
Alloy Durability rating (Table 4)	Dry unpolluted ISO C1/C2	Mild ISO C3	Industrial and Industrial marine Moderate ISO C4	Industrial and Industrial marine Severe ISO C5/C5+	Marine (non industrial) ISO C4/C5	Sea water immersion
A	None	None	None	P	None	None
B	None	None	P if <3mm	P	P if <3mm	N
C	None	P	P	N	N	N

P = protection, N = not recommended

Table 5: General protection of aluminium structures

in different atmospheres together with application guidelines.

- Cleaning by use of a degreasing agent to remove process and handling contaminants. Flame cleaning is not suitable for aluminium.
- Pre-treatment: For anodizing, etching is required to remove the oxide film to enable the electro chemical process to work. The pre treatment to ensure paint adhesion may also be done by using an etch primer, a wash primer or mechanical roughening with a non-metallic abrasive. Adhesion may also be achieved by use of a chromate conversion coating (whilst non chrome conversion coatings are preferred for environmental reasons, process management requirements are more onerous.
- Priming Coat: The pre-treated surface then receives a passivating priming coat that has a chromate (or non chromate - which requires more careful management) pre-treatment. This treatment ensures paint adhesion and may be done by etching or mechanical roughening with a non metallic abrasive. Adhesion may also be achieved by use of an etch primer or wash primer. This coat must not contain copper, graphite or carbonaceous materials. This limitation affects hull anti fouling treatments.
- Top Coat: One or more coats may be applied and the type must be compatible with the priming coat and chosen to suit conditions of exposure.
- Bituminous paints, hot bitumen or self etching epoxy bitumen also commonly

Acetaldehyde	Acetic acid	Acetic anhydride	Acetone Acrolein	Acrylonitrile Adipic acid
Alcohols	Aldol	Ammonia	Azomoniated ammonium nitrite solutions	Ammonium nitrate
Ammonium tricyanate	Aniline	Benzaldehyde	Benzene	Benzoic acid
Butyl acetate	Caprylic acid	Carbon dioxide	Carbon disulfide	Carbonic acid
Castor oil	Cellulose acetate	Cement	Cod-liver oil	Corn syrup
Creosote	Cresol	Crotonaldehyde	Cyclohexane	Cyclopentane
Cyclopropane	Dextrin	Dextrose	Dichlorobenzene	Dichloro Difluoro Methane
Essential oils	Easter gum	Ethyl acetate	Ethyl acetoacetate	Ethyl alcohol
Ethylene glycol	Fatty acids	Formaldehyde	Furfural	Hydrocyanic acid
Gasoline	Glucose	Glycerine	Helium	Hexamine
Hydrogen	Hydrogen peroxide	Iso-butyric acid	Lacquers and their solvents	Linseed oil
Maple syrup	Methyl ethyl ketone	Methyl salicylate	Mono-chloro-difluoro methane	Naval stores
Naphthalene	Naphthenic acids	Nitrocellulose	Nitroglycerine	Nitric acid (fuming-above 82%)
Nitrogen fertilizer solutions	Nitrous oxide (dry)	Nylon salts	Oils, edible	Oils, essential
Oils, fuels, lube	Oils, transformer	Oleic acid	Oxygen	Paraldehyde
Pentane	Perchloroethy-lene	Propionic acid	Petrol/Petroleum gas	Phthalic acid
Phthalic anhydride	Potassium nitrate	Propane	Propionic anhydride	Propyl alcohol
Propylene glycol	Pyridine	Ricinoteic acid	Rosin	Saltylic acid
Shellac	Sodium bicarbonate	Sodium chlorate	Sorbitol	Starch
Stearic acid	Styrene monomer and polymer	Sulphur	Sulphur dioxide	Sugar
Tall oil	Tar	Tetranitrate	Titanium tetrachloride	Toluene
Triacetin	Trichlorobenzene	Trichloroethylene	Urea	Vinyl acetate
Vinyl chloride	Water. high purity	Water (tap)	Xylene	

Table 6: Typical bulk chemicals handled in aluminium equipment

specified for protection where aluminium is in contact with building materials.

5.1.2 Metal spraying

Aluminium metal spray is used to enhance corrosion resistance and to provide a hard wearing surface. Commercially pure aluminium powder is sprayed through an oxy acetylene lance and melted onto the surface. Some of the aluminium reacts with the oxygen to form hard wearing aluminium oxide. The remainder forms a corrosion resisting surface.

Surfaces must be thoroughly cleaned, then roughened to provide an adequate key. Before spraying, the surfaces must be free from grease, moisture and other foreign matter. Commercial purity aluminium powder is normally used. Metal spraying may be used instead of; or in conjunction with; painting. The coating thickness must not be less than 0,05 mm (50 m) when a protective coating has to be applied over it. In either case the coating must be complete and undamaged.

5.2. Protective measures - chemical exposure

5.2.1 Aluminium exposure to chemicals

Table 6 lists some of the chemicals that have been successfully stored, handled or transported in aluminium equipment. This would typically involve the 5xxx series. The Aluminium Federation has extensive durability listings covering chemicals and foodstuffs in contact with aluminium alloys 1xxx, 5xxx and 6xxx series at different operating temperatures. Note: The corrosion resistance can be affected by trace elements or impurities in the chemicals etc.

5.3. Protective measures - engineering design

5.3.1 Responses to corrosion mechanisms in aluminium

These problems are best discussed by

Mechanism	Comment	Alloy effects	Environmental effects	Stress, Geometry and detail effects
General	Low rate in normal atmospheres	Protection with specific alloys	Increased rate with more demand	Better drainage assists
Pitting	self seals as product of corrosion (mainly aluminium hydroxide) 20 times pit volume	Increases with element concentration	Requires electrolyte	
Galvanic	Carbon and metals		Electrolyte present	
Inter-granular	2xxx 5xxx 7xxx	Grain boundary effect. Increases with higher tempers		
Exfoliation	2xxx 5xxx 7xxx	Increases with higher tempers		
Stress Corrosion	particularly under fatigue loads	Increase with higher tempers	Increases with more demanding environment	
Poultice	oxygen occlusion		Electrolyte present	Avoid areas where poultice can collect
Crevice <1mm	oxygen occlusion		Electrolyte present	Seal crevices with gasket or seal. Pit sealing may assist.
Fretting corrosion	transport effect			Pack clean
Filiform corrosion	underfilm on coated surfaces		Increases with higher constant humidity	Protect aluminium surface
Bacterial corrosion	Anaerobic/Anaerobic/stagnant water			Allow drainage

Table 7: Corrosion mechanisms and effects

examining the typical modes of corrosion associated with aluminium and its alloys. Geometry and detail considerations to prevent corrosion rather than to provide protection are similar to alternative metal choices and relate to the need to accommodate corrosion mechanisms. Table 7 addresses mechanisms and effects.

5.3.2 Geometric approaches to corrosion protection

Good design avoids corrosion by geometric

arrangements that exclude moisture traps and avoids crevices etc.

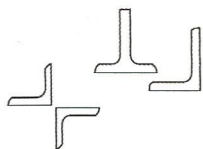
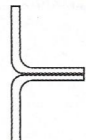
Desirable Structural Design Features

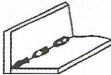
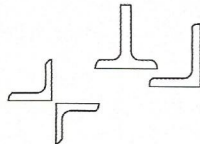
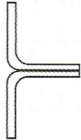
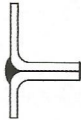
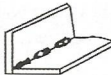
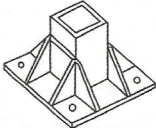
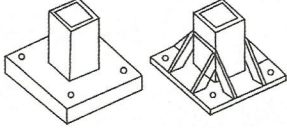
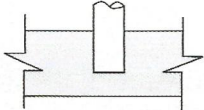
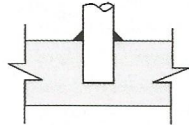
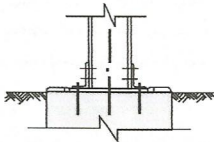
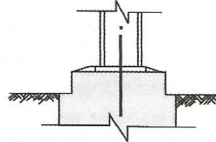
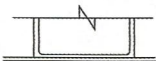
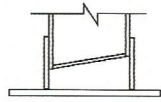
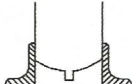
The following diagrams depict solutions to design problems and desirable design features: see Figure 5.

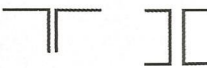
5.3.3 Aluminium to metal contact surfaces in bolted and riveted joints

Procedures, as detailed below, have been

Figure 5: Geometric arrangement to manage corrosion

1	2	3
Problem	Typical application	Typical solution
Backs of double angle cannot be painted and maintained 	Double angle truss; bearing member	Design as single angle truss; or use T-section 
Inaccessible corners on inside of lipped channel 	Purlins and girts	Use Z-section 
Potential corrosion due to angles in contact 	Angles in contact	Close crevice by sealing or welding 

1 Problem	2 Typical application	3 Typical solution
Sharp corners and discontinuous welding 	Angles and welds	Round corners and continuous welding 
Backs of double angle cannot be painted and maintained 	Double angle truss; bearing member	Design as single angle truss; or use T-section 
Inaccessible corners on inside of lipped channel 	Purlins and girts	Use Z-section 
Potential corrosion due to angles in contact 	Angles in contact	Close crevice by sealing or welding 
Sharp corners and discontinuous welding 	Angles and welds	Round corners and continuous welding 
Gussets create pockets for dirt and moisture 	Column baseplate	Design without gussets or allow drainage 
Corrosion point where member enters concrete 	Stanchion for handrail or light structure	Paint +/- 50mm above and below point where member enters concrete or provide mastic sealant covering 
Base and bolts at ground level result in water retention and corrosion 	Column bases	Column baseplate above ground level. Holding down bolts not exposed to corrosion. Stalk of column well clear of ground level. Slope for drainage. 
Plates in loose contact may encourage capillary ingress of moisture 	Service tanks or hopper sitting on structure	Locate tank or hoppers on ledge - ensure drainage  

1	2	3
Problem	Typical application	Typical solution
Insides of hollow sections not accessible for painting 	Tubular structures	Prevent entry of air by sealing with suitable welded end-plates. These can often be incorporated into the design, e.g. column base and cap plates.
Inadequate access for painting 	Adjacent structures	Provide adequate access for painting 

developed to provide protection under different atmospheric and contact circumstances. Procedures 1 to 5 are detailed below. Tables 8 to 11 show the application of these procedures to different metal to metal combinations under different operating conditions.

Procedure 1

For appearance sake the heads of steel bolts and rivets may be primed and over-coated. Otherwise no protection is required. Note that whilst pop rivets are normally aluminium, the shank may be steel. Steel shanks may corrode and leave permanent rust marks.

Procedure 2

After degreasing, both contact surfaces and the edges of bolt and rivet holes must be coated one to two head thicknesses beyond the contact area before assembly and the surfaces brought together while the coating is wet. Heads of steel bolts and rivets as well as edges of the joints, must therefore be over-coated with at least one coat of primer, care being taken to seal all crevices. When hot-driven rivets are used, paints and compounds must be cleaned from holes to avoid carbonisation.

Procedure 3

As for Procedure 2. Additional protection should be provided by using an elastomeric jointing compound (preferably of the non acid base silicone or polysulphide types) just before assembly, but after the priming coat has dried. A non porous flexible gasket may be used instead of a jointing compound if suited to joint stress transfer and operating circumstance requirements.

Procedure 4

As for Procedure 3, but heads of steel bolts and rivets and surrounding areas must, unless already metal-sprayed or galvanised, be metal sprayed, preferably with aluminium either before or after assembly. At least one priming coat must then be applied.

Procedures according to the environment						
Alloy Durability rating	Dry unpolluted ISO C1/C2	Mild ISO C3	Industrial and Industrial marine Moderate ISO C4	Industrial and Industrial marine Severe ISO C5/C5+	Marine (non industrial) ISO C5	Sea water immersion
A	1 (1)	1 (1)	1 (2)	2 (4*)	2 (3)	3(5)
B	1 (1)	1 (1)	1 (2)	2 (4*)	2 (4*)	N (N)
C	1 (1)	2 (2)	1 (2)	N (N)	N (N)	N (N)

(*) = for bolts of corrosion resisting steel only, () = ferrous bolts or rivets, N = not recommended

Table 8: Protection at joints (aluminium to aluminium.)

Procedures according to the environment						
Alloy Durability rating	Dry unpolluted ISO C1/C2	Mild ISO C3	Industrial and Industrial marine Moderate ISO C4	Industrial and Industrial marine Severe ISO C5/C5+	Marine (non industrial) ISO C5	Sea water immersion
A	1	1	2	4	3	5
B	1	1	2	4	4	N
C	1	2	2	N	N	N

N = not recommended

Table 9: Protection at joints (aluminium to zinc or galvanised steel.)

Procedures according to the environment						
Alloy Durability rating	Dry unpolluted ISO C1/C2	Mild ISO C3	Industrial and Industrial marine Moderate ISO C4	Industrial and Industrial marine Severe ISO C5/C5+	Marine (non industrial) ISO C5	Sea water immersion
A	1	2	2	4	4	5
B	1	2	2	4	4	N
C	1	2	3	N	N	N

N = not recommended

Table 10: Protection at joints aluminium to steel, cast iron or lead

Procedure 5

As for Procedure 4 except where sacrificial anodes are employed, full electrical insulation between the two metals must be ensured. The insulation material must be non-absorbent and non-conducting and extend beyond the separated areas by at least one

nut or rivet head thickness. Rivets should not be used.

5.3.4 Aluminium to metal substrates

Contact surfaces and joints of aluminium to aluminium must be protected in accordance

Procedures according to the environment						
Alloy Durability rating	Dry unpolluted ISO C1/C2	Mild ISO C3	Industrial and Industrial marine Moderate ISO C4	Industrial and Industrial marine Severe ISO C5/C5+	Marine (non industrial) ISO C5	Sea water immersion
A	1	1	2	3	3	5
B	1	1	2	3	3	N
C	1	2	3	N	N	N

N = not recommended

Table 11: Protection at joints (aluminium to corrosion resisting steel.)

with Table 8. Steel fittings must not be used for joints subject to sea water immersion.

Contact surfaces and joints of aluminium to other substrates must be protected in accordance with Tables 9-11.

5.3.5 Aluminium to other substrates

Aluminium to Copper or Copper Alloys

Contact surfaces and joints of aluminium to copper based substrates should be avoided. If used, the aluminium must be of durability rating A or B. Bolts and rivets of the copper substrate chosen. In mild environments, protection must be by Procedure 3. In all other environments use Procedure 5. Drainage of water from copper or copper-alloy roofs onto aluminium can result in severe pitting and must be avoided.

However, copper to aluminium joints are common in electrical applications as both are good conductors. Aluminium oxide in particular (porcelain) is a very good insulator, some 1024 times higher than the parent material. Oxides lead to poor conductivity and "hot spots". In this case both metals need to be protected from electrolytes to ensure good conductivity through metal surfaces to avoid the hot spots that result from the insulating oxides.

Connection is through either serrated or coned washers (Bellville) with the major surfaces protected from moisture using a conducting silicone, or by electroless plating, typically nickel. The whole joint would generally be encased to ensure a waterproof construction.

Welded Joints

Welding includes three areas of concern. These are the development of micro cracks adjacent to the weld; incomplete fusion or filler discontinuity; rough surface of welding which compromises some protection methods. All joints must be sealed against ingress of moisture prior to protection and painting up to 25mm around welds. Where welds are part of a structure that requires decoration or protection, welds should be ground smooth in the direction of the stress

prior to protection to ensure that the coating curves correctly. Where curing anticipates a coat, say, 50m thick, coverage of weld surfaces may be significantly thicker.

Adhesive Bonded Joints

Problems normally encountered with adhesive bonded joints are the result of deterioration of the adhesive or adhesion during service. Adhesive joints are only good in pure shear, tension or compression. It is important that the surface be thoroughly degreased before application. It is recommended that the manufacturer's etch preparation and adhesive application and thickness specifications be adhered to.

Aluminium in contact with Concrete, Masonry or Plaster

Aluminium needs to be protected against contact with wet uncured mortar. The pH of the wet product is 13+. Cured and dry, in dry unpolluted environments, whilst no protection is needed, the aluminium should be of durability A or B.

5.3.6. Aluminium in general applications

Aluminium embedded in concrete

Aluminium set in concrete must be of durability rating A or B. In mild environments the surfaces should be protected before embedding with at least two coats of bituminous, epoxy bituminous paint or hot bitumen. The coats should extend at least 80mm above the concrete surface after encasement.

In industrial, or marine environments at least two coats of a plasticised coal-tar pitch must be applied and the finished assembly over-coated locally with the same material, after the concrete has set, to seal the joint at the surface. Avoid metallic contact between the encased aluminium and any steel reinforcement. Submerged contact is not recommended because of lime in aggregates.

Aluminium in contact with timber

In mild environments, the aluminium should have at least one coat of protective coating

correctly applied. In aggressive environments the aluminium must be of durability A or B and be protected with at least two coats of bituminous paint or hot bitumen. The timber must also be primed and painted.

The timber must not be treated with CCA, copper sulphate; zinc chloride, mercuric salts or other preservatives harmful to aluminium.

Aluminium in contact with soils

Soils may vary between sand and clay, above or below the water table. Aluminium in contact with soils is not recommended. Where unavoidable, protection by at least two coats of bituminous paint, hot bitumen or plasticised coal-tar pitch is necessary. Additional wrapping may be used against mechanical damage.

Aluminium Immersed in water (except seawater)

The aluminium should preferably be of durability rating A, with fastenings of aluminium. The corrosivity of the water and conditions of immersion must be evaluated. Joints and contact surfaces must be completely sealed. Stagnant water should be avoided.

Aluminium is not suited to potable water plumbing piping. Potable water is treated with copper sulphate. (Brass and iron fittings may be used.) The resulting copper ions in the water result in local pitting of the aluminium. Because the pit is exposed to running water normal sealing is compromised. Through pitting may result.

Aluminium used in motor car cooling systems perform satisfactorily because of the use of corrosion inhibitors in the antifreeze coolant.

For solar heating systems aluminium should only be used in indirect systems. This avoids direct contact with potable water. As the heating element transferring heat through coolant of the same composition as is used in motor cars corrosion is avoided.

Aluminium in contact with mercury

Aluminium reacts poorly with mercury. Whilst mercury does not react to the aluminium oxide surface, scratches are inevitable. In these areas, reaction is rapid and self propagating. Marine codes prohibit the use of mercury alongside aluminium (even in instruments.) ■

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