Chapter 7

Metal coatings

Under most conditions, non-ferrous metals are more corrosion resistant than carbon steels. However, they are more expensive and, for many purposes, do not have the required mechanical properties. The advantages to be gained by combining the properties of the two groups of metals by coating steel with a non-ferrous metal are clear. Zinc has been used to coat steel articles for over a hundred years and many other examples of metal coatings are commonplace, e.g. tinplate for food cans. Metal coatings can be applied for decorative and engineering purposes, e.g. for hard facings. However, as these are not primarily for steel protection, they will not be considered here. The metals most commonly applied to impart corrosion-resistance properties to constructional steelwork are zinc and aluminium. Of these, zinc is by far the most widely used. Other metals and alloys are also used to coat steel in certain critical situations, e.g. ‘Monel’. Although they will be discussed, such alloys are not used as general protective coatings for steelwork.

The choice of metal coating for steel is determined by the cost of the particular metal, its corrosion resistance and the ability to apply it economically to the steel. The more commonly used application methods will be considered below.

7.1 Application methods

Although metals can be applied to steel in a variety of ways, including vacuum evaporation and plasma spraying, four methods are commonly used for structural steel, and the components used for construction:

(i) hot-dipping;
(ii) spraying;
(iii) electrodeposition;
(iv) diffusion.

(i) and (ii) are used for structural sections and (i), (iii) and (iv) for components and smaller items. Other methods are also used for protecting
steelwork in critical areas, in particular cladding and weld overlays. Although they are not as widely used as the four noted above, they are sometimes employed for aggressive situations, so will also be considered.

### 7.1.1 Hot-dipping

Zinc is the metal most widely applied by this method, and for heavy steel sections is the only one. Tin and lead are commonly applied by hot-dipping but not for structural steelwork. Aluminium is also applied by this method, particularly to sheet steel, which is marketed as a pre-coated product, often as Zn–Al-coated steel. Although aluminium can be applied to heavier sections of steel by hot-dipping, it is a more difficult and expensive process than for zinc and is rarely, if ever, used. However, if an economic form of this process could be developed it might well prove to be a suitable method of coating with aluminium, which, in many situations, provides a higher degree of corrosion resistance than does zinc.

Zinc is particularly suited to hot-dipping because of its low melting point (420°C) and the nature of the alloy layer formed during the process. For many years hot-dipped galvanising has been specified by BS 729:1971 (1986). A new International and European Standard BS EN ISO 1461:1999 has now been published. Aluminium is by no means as easy to apply by dipping techniques. It has a higher melting point than zinc (660°C) and this means that the bath usually has to be operated at a temperature over 700°C. At this temperature the reaction between aluminium and steel is rapid, resulting in high dross formation. Furthermore, at this temperature, because of the reaction with steel, it is necessary to use ceramic-lined tanks, which are more expensive than the standard steel type used for zinc. Aluminium oxidises readily to produce an oxide (Al₂O₃) and this makes fluxing more difficult than with zinc. Oxide particles may also become entrapped in the coating.

#### 7.1.1.1 Hot-dip galvanising

The procedures for hot-dip galvanising are as follows:

(a) Steel is cleaned of grease and oil by dipping into an alkaline or acidic degreasing solution. Welding slag, paint and heavy grease requires additional manual cleaning methods for their removal.

(b) The steel is then immersed in a bath containing acid to remove rust and scale. This is termed ‘pickling’ and is usually carried out in a dilute solution of hydrochloric acid. Blast-cleaning may be employed before pickling, either to obtain thicker zinc coatings on steel or to remove all sand from iron castings.

(c) After a further rinsing operation the steel will then undergo a fluxing
procedure. This is normally applied by dipping in a flux solution. Alternatively the steel can be immersed through a flux blanket floating on top of the molten zinc. The fluxing operation removes any last traces of oxide from the surface and allows the molten zinc to wet the steel.

(d) The steel is then dipped into the molten zinc. Large sections of steel are dipped directly into the bath. If the section to be coated is longer than the bath it may be possible to ‘double dip’ it, provided the overall length of the steel is somewhat less than twice that of the bath. Small components are either fixed in a jig or placed in a suitable perforated container, then, on removal, centrifuged to remove excess zinc and to eliminate irregularities in the coating. This reduces the coating thickness and tends to produce a matt surface; on the other hand, it removes excess zinc from threads on nuts and bolts.

(e) Sometimes further treatments may be carried out immediately after the steel has been removed from the bath. These include wiping and centrifuging to remove some of the molten metal from the steel.

7.1.1.2 Continuous galvanising

Heavy steel sections are individually dipped but wire, tube and sheet can be coated by continuous processes. To produce coated sheet, coils of thin gauge steel are degreased then treated to remove scale and rust before passing through a protective gas atmosphere into the zinc bath. The strip from the bath passes through fine jets of air or steam which remove zinc to provide the thickness of coating required. The strip emerging from the process may be cut into sheets or coiled for storage and transport prior to further coating treatments: hence the process is often called ‘coil coating’.

The continuous process is not used for heavy sections but components made from sheet may be used in structures and buildings.

7.1.1.3 Reactions occurring in hot-dip galvanising

When the clean iron or steel component is dipped into the molten zinc, a series of iron–zinc alloy layers are formed. The rate of reaction between the steel and the zinc is normally parabolic with time and so the initial rate of reaction is very rapid and considerable agitation can be seen in the zinc bath. The main thickness of the coating is formed during this period. Subsequently the reaction slows down and the coating thickness is not increased significantly even if the article is in the bath for a longer period. A typical time of immersion is about four or five minutes but it can be longer for heavy articles that have high thermal inertia or where the zinc is required to penetrate internal spaces. Upon withdrawal from the galvanising bath, a proportion of molten zinc will be taken out on top of the alloy
layer and generally cooled to exhibit the characteristic bright, spangle finish associated with galvanising.

The exception to this occurs when the steel contains in excess of 0.25% silicon. Silicon may be present because of its use as a deoxidant in the manufacturing process of steel (silicon-killed steels) or may be present accidentally, and in these instances the coating thickness continues to increase with the time of immersion in the molten zinc. For steels without relatively high silicon contents, the most important influence on zinc coating thickness formed is the mass of the iron or steel component. The higher the mass the greater the coating thickness. The thickness can be increased by grit blasting before the initial pickling process, since this provides a greater surface area with which the molten zinc can react. Galvanised coating thickness cannot be increased to any significant extent by double dipping, i.e. dipping the article more than once.

7.1.1.4 Thickness of hot-dipped galvanised coatings

The corrosion protection of galvanising is proportional to its thickness. For steel articles 1–3 mm thick, the localised coating thickness will be 60µm and the average 70µm. For steel articles 3–6 mm thick the localised coating will be 85µm and the average 95µm. For steel in excess of 6 mm, the localised thickness will be 100µm and the average 115µm. Where grit blasting is specified, for example using grade G24 chilled iron grit, the minimum thickness can be raised to 140µm. In practice, for structural steel, the minimum thickness is normally much higher than this without the need for grit blasting. When the steel contains a silicon content in excess of 0.25%, then coating thickness of 210µm or greater can be obtained. Excessively thick coatings of galvanising can be brittle and flake from the surface when the steel is under stress, so the specification and implementation of thick coatings by the use of high silicon content steel should only be used by agreement between purchaser and galvaniser and is seldom justified. It is more likely that the high silicon content, and the consequent high film thickness, will be there by accident. Threaded articles such as nuts and bolts are normally centrifuged on drawing from the bath and while the zinc is in a molten state. This reduces the zinc coating thickness and ensures that the threads remain free running. These are normally required to have a minimum coating thickness of 43µm.

7.1.1.5 Design of fabrications for hot-dip galvanising

Although fabrications can usually be galvanised without serious problems, care must be exercised in the design of the steelwork to ensure that all parts are adequately coated and that distortion is avoided.
Experienced galvanisers can advise on the requirements and BS EN ISO 14713 ‘Protection Against Corrosion of Iron and Steel – Zinc and Aluminium Coatings – Guidelines’ is available. Sections of this document deal with the important issue of design for galvanisers. Clear diagrams are included to assist designers and fabricators to achieve the optimum design of components, so that galvanising can be carried out simply, cost effectively and safely.

Venting is particularly important for enclosed spaces. During immersion in the zinc bath any liquid, e.g. from pickling, contained in enclosed areas may vaporise and the pressure may be sufficient to cause distortion or even bursting of the steel.

Distortion may also occur in the fabrication, particularly if steels of widely differing thickness are used. This arises mainly from uneven heating in the bath. Thinner materials below about 3 mm may need stiffeners to avoid distortion. At crevices and joints, acid may remain after pickling. When the fabrication is galvanised the acid may become entrapped by the zinc coating leading to attack on the steel interface under the coating.

The molten zinc must be able to reach all parts of the fabrication while it is in the bath. To ensure such flow, holes should be provided wherever necessary. It is always advisable to discuss the design with the galvaniser to ensure that adequate coating of the steel is achieved.

Dross is formed during the galvanising process from iron–zinc alloys, which, being heavier than zinc, sink to the bottom of the bath and can cause ‘pimples’ on the surface of the zinc coating. Zinc oxide forms on the surface of the molten zinc and if it is not skimmed away from the steelwork before immersion and during withdrawal it also can lead to poor appearance.

Galvanised coatings often have a bright spangled appearance but this is not an essential requirement for a good protective coating. Steels with high silicon content often produce a dull grey coating. This is likely to be thicker than the brighter coatings and provides sound protection where appearance is not important.

The general roughening of the galvanised surface may be produced in a number of ways, including over-pickling and excessive immersion times. Although not pleasing in appearance, such coatings may provide perfectly sound protection.

### 7.1.2 Sprayed coatings

When metal spraying, or thermal spraying, as it is sometimes known, is used for corrosion protection, the metals most commonly used are zinc, aluminium or their alloys. An important variation to this range is an aluminium/magnesium (95/5) alloy specified by Norwegian offshore operators.2
Metal coatings applied by spraying should not be confused with paints such as zinc-rich or inorganic zinc silicate. Although these may have a high percentage of zinc in the final coating they also contain a binder. Sprayed metal coatings are purely metallic and are sprayed directly from a gun (see Figure 7.1) onto the steel surface, so no binders or solvents are involved.

The essential features of the process are as follows. Metal in the form of a powder or wire is fed through a nozzle with a stream of air or gas and is melted by a suitable gas–oxygen mixture. The melted particles are then sprayed onto the steel surface by compressed air or gas. The particles of metal impact onto the surface and a coating consisting of a large number of these particles is formed. Such coatings are porous because they are made up of many discrete particles which are not melted together. There is no metallurgical bonding at the steel surface as occurs with hot-dipping processes. There are also no alloy layers; the coating is virtually the same composition as that of the wire or powder used for the process. Wire is now more commonly employed than powder for corrosion-resistant coatings.

Another method of application is by arc spraying (see Figure 7.2). This process is based on the formation of an electric arc immediately before the jets of compressed air. The metal is broken into a fine spray of particles by the arc and is projected onto the steel surface. The process operates at a
much higher temperature than does the more commonly used gas–oxygen system for melting the metal. Consequently, some incipient welding may occur between the sprayed particles and the steel surface. Whether for this reason alone or in combination with others, improved adhesion is obtained by arc spraying. This process is sometimes used for aluminium but not for zinc coatings.

Since the adhesion of sprayed coatings does not rely upon a metallurgical bond (cf. hot-dipping), some form of mechanical keying is required. Therefore, steel must be blast-cleaned with angular grit to provide a suitably roughened surface of high cleanliness. To ensure sufficient adhesion for aluminium, the steel must be cleaned to the highest standard, i.e. Sa3 (International scale) or the equivalent. A similar degree of cleanliness is advantageous for sprayed zinc coatings, although adhesion may be satisfactory if cleaning is to a slightly lower standard, i.e. Sa2½.

BS EN ISO 14713 ‘Protection Against Corrosion of Iron and Steel in Structures – Zinc and Aluminium Coatings – Guidelines’ gives information on the design requirements of components to be thermally sprayed.

Other thermal spray processes use plasma spray and high-velocity oxygen fuel (HVOF) equipment with powdered metals mainly to produce engineering coatings, which are designed for modification of surfaces or repair of mechanical parts.
7.1.3 Coatings produced by diffusion

Although diffusion occurs in the hot-dipping process, some coatings are produced purely by diffusion processes in which the coating metal, usually in the form of a powder, is reacted with steel at a temperature below the melting point of the metal. There is diffusion of the coating metal into the steel and some reverse diffusion of iron from the steel. Many metals can be used to provide such coatings, but only zinc is used to any extent for corrosion resistance purposes. Aluminium and chromium diffused coatings are also produced on steel but not primarily for protection against corrosion. The term ‘cementation’ is sometimes used for the method when powders of low-melting-point metals such as zinc or aluminium are used.

The process for producing zinc diffusion coatings is called ‘sherardising’. The coatings themselves are generally termed as being ‘sherardised’. Sherardising is used primarily for small components such as nuts and bolts; it is not used for the main steelwork of the structures. In this process the components are first degreased and pickled. They are then packed in zinc powder or dust, usually with a dilutent such as sand, contained in a steel drum. This is slowly rotated and the temperature is raised to just below the melting point of zinc, e.g. 400°C. The drum is rotated for some hours, depending on the size of the components, and the coating thickness required (see Figure 7.3).

![Rotating drum for diffusion process.](image)
The coating produced is an Fe–Zn alloy. An advantage of this method is that there is only a very slight change in the dimensions of the component after coating. This is particularly useful for threaded components such as nuts and bolts. Since the coating is an Fe–Zn alloy it will discolour on exposure to an atmospheric or aqueous environment, producing a ‘rusty appearance’. This does not indicate corrosion of the steel, but is unattractive. Furthermore, sherardised coatings are usually only about 25µm thick. So, for both appearance and corrosion performance, it is generally recommended that they be painted. Sherardising is the only diffusion coating process commonly employed for components used for constructional steelwork.

Aluminium coatings can be applied by a cementation process similar to sherardising. It is called ‘calorising’ and although such coatings can be used for fasteners for steelwork, they are much more commonly used to resist high-temperature conditions. ‘Chromising’ is the term used for the diffusion process used to produce chromium coatings. They can be produced from powders, from chromium halide vapours or from a combination of both. These are mainly used for oxidation resistance or for special purposes related to chemical environments, e.g. the prevention of intergranular corrosion of certain alloys.

Other metal coatings can be produced by diffusion processes but will not be considered here because they are not used for general corrosion-resistance purposes.

7.1.4 Electrodeposited coatings

Electrodeposition, or electroplating as it is more commonly known, is a process used to apply many different metals to both steel and non-ferrous metals. Many of the coatings produced are mainly decorative, e.g. silver plating. Chromium plating has been widely used for car trims and for some nuts and bolts normally used for interior purposes. However, for constructional steelwork, zinc is the metal most commonly applied by this method, usually to fasteners and other small components. The only other metal used to any great extent is cadmium, which is considered to provide better protection in some environments. However, cadmium-plated fasteners are not generally used for the bolting of heavy constructional steelwork.

The electroplating process is an electrochemical process with the same basic mechanism as that discussed for corrosion in Chapter 2. The metal to be coated, e.g. steel, is the cathode and the coating metal, e.g. zinc, is the anode of the cell. The electrolyte contains salts of the coating metal and other additions often of a complex nature. Proprietary solutions are often used for commercial electroplating. The steel must be thoroughly cleaned, usually by pickling, before it is electroplated. Components such as nuts and bolts may be plated in batches in a revolving barrel while steel wire
and strip are usually treated by a continuous process. Generally, comparatively thin coatings are produced (about 2.5 µm) and these require additional protection for exposure outdoors.

There is also a form of chemical or electrolysis plating; this is a chemical process and is widely used for nickel ‘plating’ of comparatively expensive components to provide corrosion and wear resistance. There is no alloying between the steel and the coating in either of these methods.

### 7.1.5 Other application methods

Although cladding of one metal onto another, e.g. by rolling, is used to produce stainless coatings on carbon steel, this type of coating is used more for process plants than for constructional work. Cladding is used to protect steelwork in the splash zone of offshore structures, although usually only the hot riser pipes. The cladding is generally provided by wrapping ‘Monel’ (a Ni–Cu alloy) sheet round tubular members and then welding it into place. It is a comparatively expensive method, and, if damaged, there may be ingress of seawater behind the sheeting, leading to galvanic attack on the steel.

For other critical areas of ships, process plant and offshore platforms, highly resistant but expensive metals or alloys may be applied as weld overlays. In this method the alloy, e.g. Inconel 625, is welded to the steel and then treated to produce a smooth surface. The method is normally used in limited areas, for example it has been used for trunnions on lock gates.

A summary of metal coatings used for constructional steelwork is given in Table 7.1.

### 7.2 Corrosion mechanism of metallic coatings

The corrosion protection afforded by metal coatings is basically that of an environmental barrier. Its effectiveness is determined mainly by the thickness of the coating and its ability to resist attack from the environment.

<table>
<thead>
<tr>
<th>Application method</th>
<th>Alloy layer</th>
<th>Metals generally applied</th>
<th>Structural steel</th>
<th>Components</th>
<th>General thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot-dipping</td>
<td>Yes</td>
<td>Zn</td>
<td>Zn, Al</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Spraying</td>
<td>No</td>
<td>Zn, Al</td>
<td>Zn, Al</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Electroplating</td>
<td>No</td>
<td>Nil</td>
<td>Zn, Cd</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Diffusion</td>
<td>yes</td>
<td>Nil</td>
<td>Zn, Al²</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

² Generally only for heat-resistant purposes.
Zinc is amphoteric but stable in the pH range 6–10. In air a protective layer of zinc oxide forms on zinc and in dry conditions attack is negligible. The presence of moisture leads to the conversion of the oxide to zinc hydroxide which reacts with carbon dioxide in the air to form a basic zinc carbonate. This is insoluble, so in comparatively unpolluted atmospheres the corrosion is low. However, in the presence of industrial pollutants such as sulphur dioxide, acidic surface moisture dissolves the zinc. Although basic salts are reformed, over a period of time zinc corrosion progresses and there is a good correlation between the corrosion rate of zinc and the amount of pollution in the atmosphere. Chlorides have less effect than industrial pollutants but their presence leads to the corrosion of zinc.

Zinc coatings behave in the same way as zinc metal but both hot-dipped and diffused coatings have Fe–Zn alloy layers. These are at least as corrosion-resistant as zinc (some authorities consider that the corrosion resistance of the alloy is 30–40% greater than that of zinc⁴), but they behave differently, producing a brown, rust-like corrosion product.

Generally, there is a fairly linear relationship between the thickness of a metal coating and its protective life.⁵ Metal coatings, unlike paints, corrode and it is the rate of the corrosion in a particular environment that will determine the loss of coating thickness and the period of its effectiveness as a barrier. Consequently, the lives of metal coatings are directly related to coating thickness and to the conditions of exposure (see Table 7.2). The method of application has an influence on the corrosion performance, in part because of the thickness of coating produced by the different methods and also because the nature of the coating varies with different forms of application. The most straightforward example is that of an electrodeposited coating, which is, in effect, a protective layer of non-ferrous metal with no metallurgical bonding to the steel substrate. Such coatings are usually thin and when exposed to an environment they corrode until all the coating metal has been converted to corrosion products, leaving the

### Table 7.2  Corrosion rate data for various environments taken from BS EN ISO 14713:1999

<table>
<thead>
<tr>
<th>Corrosivity</th>
<th>Corrosion risk</th>
<th>Zinc corrosion rate µm/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposed rural inland</td>
<td>Medium</td>
<td>0.1–0.7</td>
</tr>
<tr>
<td>Urban inland or urban coastal</td>
<td>High</td>
<td>0.7–2.0</td>
</tr>
<tr>
<td>Industrial with high humidity or high salinity coastal</td>
<td>Very high</td>
<td>2.0–4.0</td>
</tr>
</tbody>
</table>
steel substrate to be attacked by the environment. The period of protection will be determined by thickness of coating and the corrosion rate of the particular metal in the environment of exposure. In warm, dry interiors, the rate may be very low, so a comparatively long period of protection may be achieved. However, in most exterior or immersed environments, the life afforded by such a thin coating will be short and additional protection will be necessary. In fact, for most constructional purposes electrodeposited coatings of zinc or, where employed, cadmium, should be considered as temporary protection prior to painting.

Hot-dip coatings of zinc will initially behave in much the same way as electrodeposited coatings, because there will usually be a layer of nearly pure zinc at the surface. The thickness of this layer will vary. On continuously rolled sheet most of the coating will be zinc, whereas on many structural sections only a thin zinc layer will be present. Eventually this will corrode away leaving the Fe–Zn alloy layer exposed to the environment. Although the Fe–Zn alloy layer provides protection to the steel, the appearance is not necessarily acceptable for all structures. Therefore, for purely cosmetic purposes, some form of paint coating may be considered as a requirement. These circumstances do not arise under immersed conditions or where appearance is not important.

Diffused coatings, such as sherardised zinc, are composed virtually entirely of Fe–Zn alloy layers, so the brownish corrosion products are formed at an early stage. Furthermore, the coatings tend to be thin (12–25 μm), although thicker coatings can be obtained. Therefore, such coatings are usually applied to components such as nuts and bolts, where the change of dimensions in the threads is slight, and finally painted.

Both aluminium and zinc sprayed coatings are similar in that small globules of the molten metal strike the surface and are elongated as they solidify. Both coatings are porous but aluminium is usually somewhat more so than zinc, up to 10% although usually about 5%. Particles in the coating are surrounded by oxides but eventually there are enough discontinuities to allow sealing of the pores by the corrosion products.

Problems can arise with aluminium sprayed coatings exposed to fairly mild conditions because the steel substrate may rust slightly, producing some stain on the coating. Eventually the pores are blocked but the appearance may be affected by the rust staining. The influence of corrosion product formation may have effects on paints applied over sprayed coatings that have been exposed before painting. This is likely to be more of a problem with zinc than aluminium coatings. The presence of soluble zinc corrosion products under the paint film can lead to its premature failure by blistering and eventual flaking. In most circumstances, sealing of sprayed coatings rather than painting is recommended (see Section 7.3).

The metals commonly used to protect structural steel and the components used with it, zinc, aluminium and cadmium, are all anodic to steel.
This means that they will protect steel at damaged areas and edges of sheets. Furthermore, sacrificial protection will occur at small pores in the coating. This additional protection is clearly beneficial but is not the main reason for using such coatings: this is for overall protection of the steelwork. Sprayed aluminium coatings provide this form of galvanic protection when immersed in seawater, but it is by no means so effective with electrolytes of high resistivity, e.g. in river waters or in many atmospheric environments.

Where the protection to the steelwork is in the form of cladding or weld overlays, then over the general areas of coating the corrosion rate will be determined by that of the metal used for the particular form of protection. In the case of welded coatings, the performance will be similar to that of the cast rather than wrought form of the alloy, and these may differ. The main difficulty with cladding, where the protective metal is rolled onto the steel, arises at edges, and these must be given additional protection. With ‘wrap round’ cladding, e.g. of Monel on offshore platforms, any tear or other form of damage may allow water ingress behind the cladding. In the absence of suitable precautions such as applying a thick coat of paint to the steel, serious bimetallic attack on the steel may occur. Furthermore, of course, wrap round cladding can generally be applied only to tubular members.

### 7.3 Painting of metallic coatings

Diffused and electrodeposited coatings nearly always require additional protection, mainly because these methods tend to produce thin coatings. Both spraying and hot-dipping are capable of producing comparatively thick coatings and in many situations these will be sufficient to protect the steel for a considerable length of time, so additional coatings may not be required. Both hot-dip galvanised and sprayed coatings tend to produce a rather unattractive appearance after a period of exposure. This is more noticeable on large sections than on smaller items such as lamp posts. Some form of additional decorative coating may therefore be considered to be necessary. It should, however, be appreciated that future maintenance intervals will then be those of the metal plus paint system which is generally less than the bare metal coating, but longer than for a similar paint system applied directly to bare steel. The corrosion resistance of metal sprayed coatings can be enhanced by the application of specially formulated sealers that penetrate the pores and reduce the total area of exposed metal. Sealers not only extend the useful life of the metallic coating but provide a smoother finish and can give some colour as desired.

Sealers must have low viscosity to ensure penetration and must be suitable for the subsequent environment, e.g. aluminium pigmented silicone resin for aluminium metallic coating required for heat resistance. If further paint coatings are to be applied to a sealed metallic coating, the sealer
must be compatible with these coatings. Sealers should also be applied as soon as possible after the metallic coating application, since the spray coating is extremely sensitive to condensation and moisture which, due to the porosity of the surface, is often not readily apparent. Powdery zinc oxide films can occur on unsealed zinc and oxides with a rusty appearance rapidly become visible on unsealed aluminium.

The sealer must be compatible with the sprayed metal. Some formulations which perform well on steel, will fail rapidly on zinc or aluminium, for example straight oil-based paints, such as alkyds, are not generally satisfactory. Typical single-pack sealers are solutions of vinyl chloride/acetate co-polymers. Two-pack epoxy or urethane sealers can be used providing that, if they are to be subsequently overcoated, the procedure necessary to ensure good adhesion is fully appreciated. It is also possible that the stress developing in such materials during curing may aggravate and reveal any inherent weakness in the adhesion of the metallic coating. Some specifications call for the application of poly vinyl-butyral etch primers but these materials are sensitive to moisture in the early stages of their cure and should not be left without further overcoating.

The painting of freshly galvanised surfaces provides problems of a rather different kind. Often adhesion between the paint and zinc coatings may be poor, leading to fairly rapid flaking of the paint. This arises from the nature of the freshly galvanised surface, which is often shiny and too smooth for good adhesion of most coatings. A number of approaches have been proposed to deal with this difficulty and they can be summed up as follows:

(i) The use of sweep blasting, i.e. using low pressure (40 p.s.i.) blast-cleaning with a fine grade non-metallic abrasive, can be very effective, but only when undertaken with a high degree of expertise. It is used to best advantage on flat surfaces. Excessive blasting can remove all the zinc coating and expose bare steel, especially on edges and fasteners.

(ii) Application of a solution of T-wash, a non-proprietary formulation obtainable from many paint companies to a degreased surface. It is basically a solution of phosphoric acid in methylated spirits containing a small quantity of copper carbonate which reacts with the zinc surface to turn it black; the surface is then suitable for painting. If the surface does not turn black then the treatment has to be repeated. This method must be used with some caution because an acidic solution is involved. Furthermore, during application the T-wash reaction with the zinc produces a rather unpleasant smell. Care should be taken to avoid ponding or puddling of the T-wash and any excess should be removed by washing with water. Although widely and successfully used for many types of paint, it may not be a satisfactory preparation for two-pack epoxies and urethanes because the etching may not be sufficient to provide a good key.
(iii) After new galvanising has been exposed in the atmosphere for at least twelve months, a process in this instance called weathering, preparation of the surface for painting is much simpler. All the surface requires is using either abrasive pads or a stiff bristle brush to remove all loose material, corrosion products, etc. Care must be taken to ensure that the surface is not burnished or polished to become too smooth. Ideally this process should then be followed by a hot water detergent wash, then rinsing off with fresh clean water of drinking quality. T-wash should not be applied to weathered surfaces. In marine environments where chloride levels are high, weathering is not the preferred option.

(iv) Etch primers of a type suitable for applications to galvanised surfaces are also used. Because etch primers are fairly colourless and must be applied in very thin, wash-like films, it is often difficult to see if the surface has been fully covered. Also, major differences arise in the surface condition when single- or two-pack materials are used, the better quality of surface being achieved with the latter. The single-pack primers, although easier to use, have lower levels of reactive materials in their formulation, whereas the two-pack products carry higher levels which are activated as a result of mixing.

(v) Water-based proprietary products, claiming to aid adhesion on fresh and aged galvanising, being recoatable with either one- or two-pack materials, have recently become available.6

Generally, there are no problems in painting sherardised and electroplated coatings.

If the zinc coating has virtually corroded away leaving rusted and pitted steel, then it should be cleaned in the same way as other rusty steelwork.

Problems may arise if the zinc coating has been given a chromate treatment as a protection against wet storage stain. Such coatings are commonly applied to galvanised sheet steel but more rarely to sections. Advice should be sought from the paint manufacturers if galvanised steel has been chromated and requires to be painted.

### 7.4 Performance of metallic coatings

There is a considerable amount of data on the corrosion of zinc and zinc coatings. Where relative humidity is below 60% the corrosion rate of iron and steel is negligible, but above that level it can be 10–40 times greater than that of zinc, the higher ratios being in high chloride environments. Less data are available for aluminium coatings, although what has been published tends to show their high level of corrosion resistance. Many of the data on zinc coatings have been obtained from the exposure of zinc metal specimens, so actual corrosion rates have been obtained.

Although similar tests have been carried out on aluminium specimens, corrosion rates are not necessarily quoted as loss in micrometres per year.
because the metal tends to pit, unlike the more general corrosion of zinc (and carbon steel). Consequently, many of the test programmes concerned with aluminium coatings provide qualitative evidence of corrosion performance based on appearance. Nevertheless, this evidence is sufficient to show the excellent properties of aluminium metal coatings. In most aggressive environments they are more protective than zinc coatings of the same thickness; the main exception is under alkaline conditions.

As noted previously, coatings of aluminium and zinc alloys are produced in sheet form by continuous hot-dipping methods. Both the main groups of alloys 55 Al 45 Zn and 95 Zn 5 Al (with rare earth additions) are superior to zinc in corrosion resistance. Only limited data are available. In one series of tests the 55 Al–Zn coatings corroded about 2.2 µm/year in a marine environment, less than half that of the zinc in these particular tests. On the other hand, aluminium corroded at about half the rate of the alloy coating. However, the results are not directly comparable and the full results should be studied.7

7.4.1 Performance of zinc coatings

7.4.1.1 Atmospheric

For some years the corrosion rate of zinc was based on data supplied by the Zinc Development Association and published in the now redundant Code of Practice BS 5493 (1977). The new British, European and International Standard 14713 ‘Protection against corrosion of iron and steel in structures – Zinc and Aluminium – Guidelines’ updates this information. It points out that, in recent years, environmental legislation to control pollution of the atmosphere has resulted in a substantial reduction in pollutants, especially sulphur (see Figure 7.4). For example, the standard states that 85 µm minimum of hot-dip galvanising, 100 µm minimum of sealed sprayed aluminium and 100 µm of sealed sprayed zinc will have a typical life-to-first-maintenance time in excess of twenty years. This is for exposures as aggressive as the interior of swimming pools, chemical plants and exterior exposure for industrial inland or urban coastal areas. It also states that a similar long life can be achieved in very high corrosion risk areas such as exterior industrial with high humidity or high salinity, by increasing the hot-dip galvanised thickness to a minimum of 115 µm and sealed or unsealed zinc or aluminium metal spray to a minimum of 150 µm thickness. Even when immersed in seawater, providing that it is in a temperate climate, the Standard claims that 150 µm minimum of sealed aluminium metal spray or 250 µm of sealed zinc metal spray will also last in excess of twenty years. These corrosion rates are based on 1990 and 1995 data and even lower rates of corrosion can be expected in the future as pollution continues to fall.
Zinc corrosion rates are represented by three categories indicated by the colour codes shown below.

<table>
<thead>
<tr>
<th>Corrosion category</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average corrosion rate (µm/year)</td>
<td>0.5–1</td>
<td>1.5</td>
<td>2–2.5</td>
</tr>
<tr>
<td>Average life of 85 µm galvanized coating (years)</td>
<td>170–85</td>
<td>57</td>
<td>43–34</td>
</tr>
</tbody>
</table>

Figure 7.4 1999 MAFF Chart, typical UK corrosion rates for zinc.
Source: UK Galvanizers Association.
A publication on behalf of the UK Galvanisers Association\(^6\) gives corrosion rates obtained from the exposure of zinc metal specimens at regular intervals throughout the UK. Based on several of these surveys, it could be estimated that a typical 85\(\mu\)m hot-dip galvanised coating has an average lifetime of between 40 and 50 years. Since the corrosion resistance of zinc is roughly proportional to its thickness, other methods of application, such as electroplating or diffusion (sherardising) will give proportionally shorter lives.

### 7.4.1.2 Immersion in seawater

The corrosion rate in seawater is about 15–17\(\mu\)m per year. A range of tests has shown corrosion rates from 10–25\(\mu\)m per year. In the splash zone, higher rates of corrosion may occur, particularly on some tropical and surf beaches where inhibiting magnesium salts may not be present in the seawater. In most natural waters zinc performs well, but this is to some extent determined by the formation of protective scales, so corrosion will be higher in soft waters.

### 7.4.2 Performance of aluminium coatings

Tests carried out in an industrial environment in 1967 indicated that aluminium coatings gave even longer maintenance-free lives than those based on zinc. For constructional steelwork only sprayed coatings are of direct interest. Based on tests carried out in the industrial environment at Sheffield, aluminium coatings are usually more resistant than those of zinc. This is confirmed in the American Welding Society 19-year tests where, in many environments, aluminium was still protecting the steel over this period. In seawater immersion tests, sealed aluminium coatings of thickness 150\(\mu\)m were still protecting the steel after 19 years, although there was evidence of corrosion of the aluminium. Zinc coatings did not protect the steel for this period when immersed in seawater. Even under alternate exposure to the atmosphere and seawater of splash-zone conditions, the sealed aluminium coatings over 80\(\mu\)m in thickness performed well.

In tests carried out on hot-dip aluminium specimens,\(^7\) again aluminium, and incidentally 55% Al–Zn coatings, performed much better than zinc coatings.

### 7.4.3 Performance of cadmium coatings

The corrosion rates for cadmium in different environments have been established in a number of test programmes.\(^9\) Typical corrosion rates in micrometres per year are as follows: industrial, 10.2; urban, 2.3; and marine, 1.3.
7.5 Comparison between metallic and paint coatings

A number of points must be taken into account when considering metal coatings as the method of protecting steel. The obvious comparison is with paint coatings, but even where metal coatings have been selected, the choice of metal and, in the case of zinc, the method of application have to be considered. Compared with paint coatings there are advantages and disadvantages; these can be summarised as follows:

ADVANTAGES OF METAL COATINGS

(i) Application is more straightforward than with paint systems and is more easily controlled.
(ii) The life is more predictable and, usually, premature failures do not occur.
(iii) Handling is easier because there is no requirement for drying and metal coatings resist damage to a greater extent.
(iv) If damaged there will be sacrificial protection by the coating metal. This is more certain with zinc than with aluminium coatings.
(v) They have good abrasion resistance. Considered to be a factor of 10 or more than most conventional paint systems.
(vi) Unlike paint coatings, they generally have a thick coating on edges.
(vii) Standards exist for most metal coatings and this makes specification more straightforward and ensures a higher level of certainty of performance.

A particular advantage of hot-dip zinc coatings is that faults in the coating are readily detected. This is not, of course, the case with paint coatings, nor are faults so readily detectable on sprayed metal coatings. On hot-dip and sherardised coatings there is a metallurgical bond with the steel, ensuring the highest level of adhesion.

DISADVANTAGES OF METAL COATINGS

(i) If the metallic coating is thinner than the recommended thickness for a particular environment or if decoration is required, the metallic coating has to be painted and this is probably a more difficult operation than the application of paint to steel.
(ii) Where welding is carried out after the metal coating has been applied or where severe damage to the coating occurs, it is difficult to treat such areas to provide the same standard of protection as the rest of the structure (Figure 7.5). (Similar problems also arise with paint coatings.)
(iii) With hot-dip galvanising there is a limit to the size of fabrication that can be treated and a limit on the availability of galvanising
plant. Also the smaller the section the thinner the zinc coating, which inevitably leads to fixings, nuts and bolts, etc. having poorer protection than the main structure.

(iv) Without additional protection, metal coatings often develop an unattractive appearance.

ADVANTAGES OF PAINT COATINGS

(i) Painting facilities are widely available in shops and on-site.
(ii) A wide range of colours is available and paint coatings can provide a high cosmetic appearance, e.g. gloss.
(iii) A range of materials is available for different requirements. Unlike metallic coatings, paint coatings are available with good resistance to acidic conditions.
(iv) There are no limits on size or type of structure.
(v) Paint application is generally straightforward.

DISADVANTAGES OF PAINT COATINGS

(i) The main disadvantage of paint coatings arises from the application process. This provides endless opportunities for poor workmanship which can often not be detected after the next stage in the process has been completed. This can, however, be taken into account by adopting suitable quality control procedures.

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It is often difficult to predict the life of paint coatings. Even where standards or specifications for paint are available, they do not provide the same degree of certainty regarding the product as do standards for metal coatings.

### 7.6 Choice of type of metallic coating

For all practical purposes the choice of metal coating for structural steel sections lies between sprayed aluminium, sprayed zinc and hot-dip galvanised zinc.

The advantages of spraying over hot-dipping arise from the limitations in size of the galvanising bath and the ability to spray metal coatings on-site, although in practice this is rarely done. Hot-dipping is more easily controlled and, if steel is blast-cleaned, reasonably thick coatings can be applied. Problems can arise if freshly galvanised steel is to be painted, but these problems can be overcome. In most circumstances, hot-dip galvanising would probably be preferred to sprayed coatings if only because of the difficulties that may arise from painting sprayed coatings after some years of exposure. Sprayed aluminium coatings have been shown in tests to provide a high level of corrosion protection to steelwork, and although such coatings have been applied to structures quite successfully, there are many fewer coated with aluminium than with zinc. Nevertheless, it is somewhat surprising that so few structures are coated with aluminium in view of its corrosion-resistance. This may arise in part because the amount of aluminium used for coatings is a very small percentage of the total use of the metal; therefore, there is no great incentive on the part of aluminium producers to encourage its use.

This is quite a different situation from that concerning zinc, where the use of the metal for coatings is a significant percentage of the total production. Consequently, more data are available and a considerable amount of marketing is carried out. The standard of surface preparation probably has to be higher with sprayed aluminium than with sprayed zinc coatings to ensure satisfactory adhesion.

The choice between hot-dip galvanising and sherardising for components such as nuts and bolts is not clear-cut. The advantage of sherardising is the control of tolerances, particularly useful for threaded components. However, the method is more expensive than hot-dipping for equivalent coating thicknesses. Generally, fasteners are painted and the sherardising coating provides a suitable surface for paints.

Electrodeposition is only economic for very thin coatings. For exterior application, such coatings should be considered as providing temporary protection prior to painting.
7.7 Treatment of welded areas

Where metal coatings are applied after fabrication, welded areas can be cleaned and treated in the same way as the rest of the steelwork. However, where field welding is required, welded areas must be treated on-site. Although the most satisfactory way of dealing with welds would be grind them, then blast clean and metal spray with zinc, this is often not practicable and is rarely carried out. The usual way of dealing with welded areas is to clean them, often by wirebrushing and scraping, and then to apply a zinc-rich paint. The application of a suitable thickness of a zinc-rich paint to a blast-cleaned surface provides a reasonable measure of protection although, in many situations, less than that of the metal coating. However, application of the paint to a surface that has not been well prepared will result in early breakdown at the weld areas. This reduces the advantages of using metal coatings for long-term maintenance-free protection. Usually, the areas in the vicinity of the weld are not metal coated, or the coating is removed before welding.

To protect the weld areas of hot-dip galvanised steel, a fusible stick, similar to solder, can be applied to the area after suitable cleaning. This can be an effective method but is rarely used.

7.8 Wet storage stain

A white, porous, powdery deposit may appear on zinc surfaces. This is often called ‘white-rusting’ and occurs, usually on freshly galvanised surfaces, as a result of wet or damp storage conditions. This type of corrosion is most likely to occur with sheets that are not properly stored but can also manifest itself with components such as steel angles and occasionally even on sections.

In freely exposed atmospheric conditions, zinc coatings corrode to produce zinc oxide and zinc hydroxide, which is transformed by carbon dioxide in the air to basic zinc carbonate. Where, however, there is restricted access of air, and moisture or condensates are present on the surface, the basic carbonate may not form. Typical situations are the crevices formed by sheets closely packed together. The ‘white-rust’, basically a layer of zinc oxide and zinc hydroxide, is voluminous, up to 500 times the volume of the zinc from which it is produced. It does not adhere well to the zinc, so while any moisture is present, oxygen is available for the corrosion process to continue. This form of attack does not usually occur on zinc that has been weathered and so has a protective carbonate layer.

Although white-rusting often appears to be serious, there is usually only a slight attack on the zinc coating. This may be sufficient to cause
problems with thin electroplated coatings but not generally with hot-dip coatings. Proper storage conditions will avoid white-rusting attack by ensuring that moisture does not come into contact with freshly galvanised surfaces; steel items should be arranged so that they are well ventilated with a good flow of air.

Sheets cause a particular problem because there is a tendency to stack them together; protection against storage stain may be provided by chromating the zinc surfaces after galvanising; such treatments often produce a yellow-green appearance on the zinc. Advice should be sought from paint manufacturers regarding the adhesion of their products to such treatments.

7.9 Fasteners

There are clear advantages to be gained from using metal-coated fasteners even for painted structures. Steelwork is often painted in the shop, with a final coat being applied on site after erection. If bolts are used then, if they are given just the final site coating, which often happens, the paint will fail on the fasteners after a comparatively short period. Additionally, if black or pickled steel bolts are used, they may well rust before the site coat is applied. The use of sherardised or hot-dip galvanised nuts and bolts will overcome such difficulties.

7.10 Health and safety matters

7.10.1 Hot-dip galvanising

It is necessary to be cautious about touching items from the galvanising bath because they can stay hot for a long period. During the galvanising process it is not uncommon for splashes of molten metal to be ejected from the bath at great speed. For example, this can be due to water vapour in a hollow section expanding rapidly.

7.10.2 Metal spraying

The quantity of dust evolved in the metal spraying depends upon the efficiency of deposition. For example, the very high amperage used with arc spray produces large amounts of unstable energy where the wire is being melted and this results in a non-uniform spread of the metallic particles. The same thing happens if the flame in the gas spray method is not controlled correctly. In both instances the molten wire particles deposited on the surface will cool in the atmosphere and form dust. The dust creates a respiratory hazard for metal spray operators and respiratory protective equipment must be used. Full breathing apparatus enclosing the head is
the only acceptable protection when arc spraying and full visor protection is also required when gas spraying.

A further hazard occurs with high concentrations of dust, which can be explosive and flammable. This is particularly so with aluminium and airborne concentrations. As little as 35 mg/m³ have been known to result in explosion and fire when subjected to a source of ignition. The actual concentrations at which the mixture may become explosive will vary and depend upon particle size. The size from a spraying operation can vary from sub-micron, which is respirable level dusts, up to 50 µm. As a general rule the larger the particle size the greater the concentration required to become explosive.

The dust hazard may well only become apparent when the spraying operation is over and the dust has settled. Also the dust hazard can be aggravated by the very operation of trying to clean it up. Extraction is the method normally used to maintain dust levels below the explosive limits and the possibility of dust build-up in the extraction ducts is something that must be taken into consideration.

Ultraviolet light from the arc spray process can damage the eyes in a very short time without the operator being aware of the problem immediately. Dark glasses, or visors, similar to those used for welding, should be worn by the operator and anyone else in the vicinity.

Both arc and gas spray create a considerable amount of noise. It varies with the number and types of equipment being used and the confinement of the working area, but for example two operators working in the same area using arc spray have been recorded at 115 dB and with gas spray at 100 dB.

The metal spraying process releases a quantity of ozone, which is toxic, but generally not considered harmful to the operator in this instance. However, there is a possibility of absorption of fumes through the skin or even skin penetration by particles must be considered a real risk. Therefore all exposed extremities of the operator’s skin should be adequately protected.

Overexposure to fumes from both arc and gas spray zinc can cause flu-like symptoms, along with irritation of the eyes from the arc, skin rash due to penetration by metallic particles and sunburn symptoms due to secondary radiation.

During metal spraying, the metallic dusts could cause short circuits with electrical equipment and therefore appropriate earthing and circuit breaking measures should be ensured.
References