STEEL surface in every day environment is unstable. In absence of some kind of protective covering, electro-chemical action takes place in the presence of moisture, which transforms iron particles into brittle flaky material which we call rust. This transformation could accelerate under certain conditions. The life of sheet material which has largest exposed surface area in relation to its volume, is seriously affected if used unprotected. The importance of protecting sheet material therefore is equally high as that of its production. This is more so in India where there is shortage of all flat products.

Coatings

Depending on the requirements of the end-uses and costs, steel is protected by organic, metallic, ceramic and composite coatings by coating methods including spraying, painting, cladding, dipping, electroplating and vapour plating. Amongst the metallic coatings, zinc and tin have been traditionally in major use as coating materials for steel. Aluminium as coating material on steel is comparatively recent.

Aluminium coated steel

Aluminium coated steel is, of course, not new and untried material. It is being used widely in U.S.A. and U.K. since more than twenty years and since recently in Japan where aluminised steel tubes are also manufactured for petrol refineries. The taming of aluminium as a coating material, with its affinity particularly for oxygen, for continuous aluminising lines presented problems which till the last decade could not be solved satisfactorily with the result that both the production and costs were the limiting factors to its popularity. The search originally for a suitable material for auto-silencers was responsible for initiation of production of aluminised steel in U.S.A. Its production has been making rapid strides since the last decade and the uses cover wide fields of building industries, transport and numerous industries where the proved superior product-properties are best exploited with cost-economies and service advantage. Both the main steel producers and the processors are increasing their aluminising capacities in U.S.A. and U.K.

Production processes

Several methods of producing aluminised steel sheet and strip have been tried including powder coating, composite rolling of aluminium and steel, metal spraying and vapour coating. The only processes, in large scale use, however, at the present time, are based on hot-dipping.

(a) Large tonnage of hot-dipped aluminized steel wire is produced in U.S.A. As has been abundantly proved by the tests carried out by the National Metallurgical Laboratory, it has excellent weathering properties and has been used particularly for low voltage power lines, ACSR core and fencing in U.S.A. since a long time, even though they never have had any problem of zinc as we have. Both the Industry and the Government have a serious responsibility of ensuring that the avoidable waste of foreign exchange on zinc imports for this purpose should stop immediately.

(b) As for the wide width sheet aluminising, several hot-dip processes are in existence and are efficiently worked. The production however on batch aluminising of commercial width is slow and uneconomical. The continuous aluminising of steel strip plants however, are based on well-known Sendizimir and Whitefield processes with variations in plant and process details to suit individual requirements.

Grades of aluminium coating

Two grades of coatings are commercially available. One has a pure aluminium and the other an aluminium-silicon alloy coating. The total alloy thickness is of the order of 0.001 to 0.015 inch, equivalent to about 0.2 oz. per square foot of surface. The presence of silicon is useful in improving formation properties and ductility of the coated sheet. On the other hand, the pure aluminium coating is better where resistance to atmospheric weathering is concerned. Further improvement in structure can be obtained by cold reduction of aluminised sheet. 60% reduction gives sufficient ductility to allow even crown-type bottle seals to be made of it.
Some critical production aspects

(i) Line speed

The production line speed of 14 feet per minute in the aluminium thickness is self-controlled and there is no problem of aluminium draw. This speed however is not economical. The requisite commercial production speed of 60 to 80 ft. per minute will draw excessive aluminium and therefore exit rolls are essential.

(ii) Iron contamination

This requires to be carefully watched and avoided since aluminium attacks all metals and the products can be quite unsatisfactory. The iron enrichment of the aluminium coating and formation of iron-aluminium intermetallic compounds could be strongly cathodic to aluminium and under corrosive conditions, can lead to premature failure of the protective coating by penetration mechanism.

(iii) Aluminising temperature of steel strip

This requires to be controlled to avoid excessive heating of aluminising bath.

(iv) Pre-treatment of steel strip

(a) The unstable steel surface gets readily contaminated by oxides, rust or oils used for rust prevention during transportation and storage as also by lubricants used for fabrication. For the preparation of the steel surface for the application of the protective coating, the surface must be entirely freed from the contaminants. The degree of cleanliness required depends on the type of coating to be applied.

(b) With metallic coatings all contaminant films must be removed to obtain adherent bonding of the coating with the base metal irrespective of the form of the coating, i.e. solid state as in cladding; liquid as in hot-dipping; vapour as in vacuum deposition; ion as in electroplating and chemical displacement; or gaseous compound as in vapour plating. Aluminium however is particularly intolerant of impurities and demands exacting pre-treatment of base metal.

(c) Acid pickling for the removal of scales and oxides and alkali degreasing are commonly used for cleaning the steel surface. The multistep nature of operation and the contaminants the liquids themselves leave, preclude the desired cleaning efficiency, despite the inclusion of mechanical scrubbing, electrolytic current and electronic vibration in the liquid systems.

(d) Gaseous cleaning closely approaches the perfection. The volatile contaminants are burnt off the steel surface and oxides converted to metallic iron in the reducing atmosphere. This advantage of the cleaning, however, is available only to the processes where the coating is applied immediately after the reducing step, without the base metal being allowed to come in contact with the oxygen in the air. The continuous steel strip aluminising plants find the cleaning particularly helpful in obtaining products of satisfactory standards with coating thickness controlled within narrow limits.

(v) Composition of aluminium bath

This has been having considerable attention in U.S.A. and U.K. and alloys are available to produce coatings of specific properties. Silicon is commonly used to reduce the alloying rate and this is the most widely employed alloying addition. It improves the forming properties and the ductility of the coated steel. Pure aluminium however is better where resistance to atmospheric weathering is concerned. A 2% addition is generally considered sufficient. It also reduced the unevenness of the interfacial layer of iron-aluminium compound.

(vi) Composition and control of aluminium coating

The coating consists of pure aluminium and a layer of iron-aluminium phases below it. The pure aluminium and the iron-aluminium alloy phase which constitutes about 20% of the coating thickness is readily distinguished. The latter conforms roughly to the composition FeAl₃, though since phases have a range of composition, it is not correct to regard them as compounds in a chemical sense. This alloy phase is formed as a result of diffusion.

The interfacial layer of iron-aluminium compound has a series of loops. It is not even layer, indicating that preferential diffusion takes place at specific points. The general principles of coating formation are:

(a) The pure aluminium phase increases in thickness as the speed of withdrawal from bath increases.

(b) The alloy phase increases in thickness (at a given temperature) in proportion to the square of the immersion time.

(c) The alloy phase grows, after the work is withdrawn from the bath at the expense of the pure aluminium phase, by the amount governed by the rate of cooling.

The lesser the thickness of the sheet, the lesser the alloy growth, because it has less heat capacity than...
heavier gauge sheet. Since the health hazard associated with beryllium cannot permit its use, silicon is used to assist the control of the alloy growth.

Nature of protection offered by aluminium coating

Generally speaking the position of aluminium in relation to that of steel in the galvanic series should provide sacrificial protection to the base metal, just as zinc does. The protection offered by aluminium to steel, however, is not strictly speaking of a sacrificial nature. Zinc is usually anodic to steel under normal conditions and is capable of some degree of sacrificial protection. Aluminium, in many cases, should behave similarly, but it infrequently does so in practice because the electro-chemical action is prevented by the insulating protective skin of aluminium oxide which forms on the aluminium surface. Sacrificial action is most likely to occur in the circumstances where the layer is prevented from forming by the corrosive environment.

The thick oxide film acquired by aluminium under most conditions, protects the aluminium which in turn protects steel. The protective value of the aluminium coating depends on the corrosive environment and on the interaction of corrosive media with aluminium oxide, aluminium, steel, and corrosion products.

Protection at sheared edges and discontinuities

Where the surface coating suffers any mechanical damage, the exposed steel base continues to be protected due to electroweak or sacrificial protection provided by the coated metal. The aluminium coating further causes the formation of subsidiary protective layers on any exposed zone as well as on the aluminium coating itself, thus reducing the rate of corrosion. Tightly adherent corrosion products such as are formed in normal atmospheric exposures will protect steel at the sheared edges or at any small coating discontinuities. Sheared edges will show slight rust but since spreading is most effectively restricted and there is no lifting of the aluminium coating, this is usually of minor importance. The amount of rust depends on the type of atmosphere and metal thickness. It is less with thin sheets and is not superficially noticeable. Exposure tests and in-service uses over years have indicated that there is no blending and that the coating is not undercut.

Properties of hot-dip aluminised steel and applications

Aluminised steel combines the surface characteristics of aluminium with the strength and economy of steel. Hot-dip aluminised steel has many applications where a metal, capable of withstanding elevated temperatures and corrosive conditions, is required. In this respect, its performance approaches that of alloy steel, but it costs much less.

(a) Heat resistance

The outstanding resistance of aluminium coated steel to elevated temperatures is the result of the formation of oxides of aluminium and a series of inert iron-aluminium complexes and solid solutions which are adherent and refractory in nature. They withstand the deleterious high temperature attack. Tensile tests carried out on panels after 2000 hours of heating at 500°C to 800°C, resulted in no fracture of the alloy surface thus formed. Therefore even after complete transformation by heating the coating can take deformation without damage. It does not discolor at temperatures up to 480°C. The length of service life depends on service temperature, aluminium content of coating and the thickness of steel.

This most important property renders aluminised steel a perfectly satisfactory and economical substitute in many applications that require expensive alloy steels. Furnace and oven casings or linings, high temperature extraction ductings, heat treatment containers, laundry and canteen equipment, stoving ovens, autosilencers and exhaust systems, domestic heating appliances, heat exchangers, radiant type reflectors for gas and electricity, textile driers and numerous other industrial applications would find aluminised steel a material usable with service and cost advantages.

(b) Atmospheric corrosion resistance

In many environments, there is no doubt that aluminium coatings are superior to zinc. The most noteworthy example is the resistance of aluminised coating to a heavily polluted sulphurous industrial atmosphere, where a zinc coating would be eroded to destruction in a relatively short time. This greater durability of aluminium coating is attributed to two factors:

1. Aluminium covers itself with self-healing oxide skin which tends to protect it from corrosive environments; zinc corrosion salts are less adherent and more soluble.
2. In the circumstances where corrosion products form, those derived from aluminium are denser than the corresponding zinc salts and inhibit further attack more effectively.

The tests carried out over long periods by the American Society of testing materials as also by the Armco Steel Corporation and The National Metallurgical Laboratory, here, by exposure of aluminised samples to all types of atmospheric conditions, conclusively establish that the service life of aluminised coatings is in any case not less than two and half times that of zinc coating of equal thickness. The appearance of weathered aluminised is preferable to zinc which becomes blackened and pitted in an industrial atmosphere and in a marine atmosphere covered with a dense encrust film of basic zinc chlorides. Resistance to humid conditions is greater than in the case with zinc coatings, particularly when any degree of heat is involved.

(c) Heat reflectivity

(a) Another desirable property of aluminised steel is
its ability to reflect 80% of incident radiant heat. This renders the aluminised sheet a particularly advantageous material for roofing, siding, building panels, and other building elements under Indian conditions where summer temperatures can be maintained at comfortable levels. Cooling costs would be lower in summer. Conversely, aluminium-coated inner surface of roofing and siding helps retain heat during winter months.

(b) Resists fire damage

The unique combinations of properties possessed by aluminised steel provide excellent resistance to structural damage by fire. At 1000°F, aluminised steel has ten times the strength of aluminium at the same temperature. This property together with its retention of attractive appearance and heat reflectivity at temperatures up to 900°F render the aluminised sheets ideal for roofing, siding, roof deck, insulation lagging, weather shields, doors of all kinds and other building elements.

(d) Thermal expansion

Aluminised steel has not only low co-efficient of thermal expansion (0.0000067 inch per inch per °F) but its high heat reflectively keeps metal temperature low. Fewer expansion joints are required than for aluminium. Less total movement from repeated expansion and contraction due to temperature changes minimises possibility of tearing at fastenets or causing fatigue failures.

(e) Fabrication properties (Formability)

Aluminised steel withstands moderate brake and roll-forming. It can be bent over a diameter equal to twice its thickness without flaking or peeling of aluminium coating or damage to base metal. It can be spun and embossed but is not suitable for deep drawing operations.

(f) Mechanical properties

(a) When steel is coated by hot dipping, there is some change in the physical properties. The tensile and the elongation at break are both reduced. This is in part due to small dimensional reduction arising from the solvent action of the coating metal and its replacement by a metal inferior in tensile strength and ductility, but it is mainly a result of the presence of one or more intermetallic alloy phases. Not only these phases are hard and brittle but the interface between the alloy phase and the steel is microscopically rough and provides an abundance of points from which failure may be propagated. In aluminising, however, there is some relief of work hardening due to the temperature involved.

(b) Because of its good strength and modulus of elasticity it is easy to design economical structures that are strong and rigid. Design is further simplified because the properties conform to the standard design manual data for light gauge cold-formed steel sheets. The mechanical properties of aluminised steel accent the advantages of mating it with steel. The aluminised steel has tensile strength of 54,000 psi, yield strength 40,000 psi, elongation 22% in 2' and modulus of elasticity 29,000,000 psi. The intermetallic compound has the strength of about 15,000 psi and can withstand shearing stress of 7,000 psi. The strength is retained at elevated temperatures.

(g) Thermal shock resistance

Aluminium coated steel has shown to have about double the thermal shock resistance of uncoated base metal. The ability of aluminium alloy formed to resist attack by corrosive constituents present in some fuels, added to its naturally great resistance to oxidisation at elevated temperatures, accounts for the outstanding thermal shock resistance.

(h) Electrolytic corrosion

The inseparability of the aluminium bonded to base steel by hot-dipping process prevents electrolytic corrosion at the interface.

(i) Thermal conductivity

The thermal conductivity of aluminium increases with increase of temperature, while that of copper decreases as temperature increases. Aluminium’s thermal conductivity is more than four times that of steel or cast iron. This property of aluminium coating renders the aluminium coat sheet material immensely useful in heat transfer applications. There is no measurable resistance to heat flow across the bonding layer. There is no expanding away of aluminium from steel as in mechanical joining.

(j) Appearance and suitability for painting

Aluminised steel is not subject to white rusting, and can readily be tinted shades of green and gold by simple dipping chromating treatments. Aluminised steel has normally pleasing, satiny appearance and it does not require as exacting a surface preparation before painting as is required by galvanised steel. Aluminised steel is therefore also superior in this respect.

(k) Welding

Any of the standard methods of welding can be used to join aluminised steel. Since welding heat damages a portion of protective coating in weld area, resistance welding is preferable wherever practical. Spot welding is especially suitable. In case of fusion welding, metalising of weld areas would restore corrosion resistance. In conclusion, aluminium coated steel has considerable versatility. It is rapidly gaining in prominence. It is
finding its place as the most economical material in a variety of applications and has the potential of rapid growth. The rate of growth, however, of such relatively new grade of products depends on promotional efforts to bring the new product to the attention of the prospective buyers and to prove that using the product would be to their advantage. For India, speediest production of these aluminised sheets, assumes immense importance not only because large foreign exchange expenditure on zinc imports would be saved on regular basis but also because of the long-term cost economics and advantages associated with the use of aluminised sheets in the place of galvanised sheets.

**Economics of substitution**

**Special conditions in India**

The known zinc ore resources of India are small and, therefore, even the long-term availability of zinc is limited. This fact, in the context of mounting yearly requirements of zinc, half of which goes for galvanising, demands that alternative substitute indigenous material be considered if the severe drain on the available scarce foreign exchange resources has to be reduced. The limiting factor of foreign exchange will for a long time to come, limit the supply of galvanised sheets. The estimated short-fall of zinc at the end of Fourth Plan would be about 1 50,000 tons.

We have here a permanent solution to this difficult problem, in the use of indigenous aluminium whose immediate and long-term availability is comfortable and which, as a coating material on steel has proved its superiority in most respects for the end-uses conventionally served by galvanised material.

If countries like USA which have no problems of zinc, find aluminised steel as a better, more versatile and economical material for conventional roofing and siding and building elements, the conditions in India are all the more strongly valid for its adoption.

**Costs**

Aluminised steel sheet is somewhat more expensive to manufacture than zinc coated material, but not unduly so. As regards the cost of the coating material, there is little difference because the higher value of aluminium is offset by its lower specific gravity (2.7 compared with 7.1 for zinc). Furthermore, a ton of aluminised steel sheets has a greater volume and surface area than a ton of hot-dipped zinc coated sheets.

Aluminising production costs however, are higher for several reasons.

In the first place, the preliminary surface preparation is rather more critical because aluminium is less tolerant of surface imperfections in the pre-treatment cycles and the purity of the bath must be relatively high as iron contamination has an adverse effect on the product-values.

In the second place, the higher operating temperatures of the aluminising bath increases the heating cost of the process. To raise a ton steel to the temperature of molten zinc requires 2.3 therms: the heat needed to raise the same amount of steel to aluminising temperature is 3.5 therms. The radiation and convention losses from molten surface are also more than doubled.

Finally, the aluminising plant costs are significantly higher, while zinc galvanising bath is normally constructed from mild steel, an aluminising bath must be made from special materials and the heating techniques used, such as induction melting, also involve higher plant and power costs.

To illustrate this point, a comparative base cost in (rupees equivalent) per lb of commercial quality material in America is shown in Table I.

<table>
<thead>
<tr>
<th>Material</th>
<th>Paise per lb.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Rolled Steel Strips</td>
<td>31</td>
</tr>
<tr>
<td>Galvanised Steel Strips</td>
<td>36</td>
</tr>
<tr>
<td>Aluminised Coated Steel Strips</td>
<td>46</td>
</tr>
</tbody>
</table>

The acceptance of aluminised steel must therefore be developed on the basis of quality.

**Economics of substitution**

(i) The higher cost of aluminised steel are more than offset by higher service performance. The service life of aluminised sheets being at least 2½ times that of galvanised sheets, the long-term cost would permit a substantial saving to the consumer. His maintenance costs would be reduced. There is no question therefore, of consumer sacrifice. Decidedly, a better product at low cost is placed in his hands. Besides the nation will save large valuable foreign exchange every year.

(ii) The ready availability of indigenous aluminium will permit planning of desired expansion of the production facilities of aluminised sheets to the extent necessary to meet the large and growing demand, particularly in rural areas. Reliance on uncertain zinc imports restricts production. Wasteful recourse to the use of naked sheets need not be taken. Available scarce resources would be put to the best use.

(iii) The reflectivity of aluminised sheets up to 80% of the incident radiant heat renders them ideal as roofing materials under Indian conditions. Interiors are kept cooler in summers. The substitution is, therefore, advantageous by way of cost-economy, comfort and utility.
(b) Asbestos cement sheets

A considerable amount of foreign exchange is spent on import of asbestos fibres for the manufacture of asbestos cement sheets. The preferential acceptance of better and less costly (initial and long-term) products would substantially reduce the consumption of A.C. sheets and thus save appreciable foreign exchange.

(c) Special steels

Wherever stainless and other alloy steels are used in heat applications and where technically their replacement is feasible, aluminised steel sheets would be used with advantage and cost-economy. This is a field of potential saving of foreign exchange which may be quite important.

(d) Tinplate

The fact that sizeable cold-reduction of aluminised steel imparts to the material, the ductility of crown-cork seal material, points to the potential substitution of tinplate in applications where there is no harmful chemical reaction between aluminium and the packed material. Tin imports pose equally a serious problem.

The timely bold decision of the Government of India that no future steel complexes would be permitted to have the galvanising facilities and that even the existing plants will have to endeavour to convert the galvanising lines into aluminising lines is to be congratulated.

With a view, however, to assisting and expediting the growth of the predominantly import-substitution industries like aluminising, it is high time that the Government made an unambiguous declaration to the effect that all such industries will be accorded the status of priority industries. For, unless this is done, the growth of these industries will be frustratingly delayed due to administrative and financial complications, thus defeating the very purpose of scientific development and the national objectives cherished by us all.