COIL-ANODIZED ALUMINIUM – THE NATURAL FINISH FOR DESIGNERS AND ARCHITECTS

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INTRODUCTION

Anodized aluminium is used in a wide range of applications including structural components for aircraft, sub frames for cars, lithographic plates, capacitors, lighting reflectors, housings for audio systems, kitchen products and many decorative items. Its use in building facades is the largest application by volume and may be the oldest. Anodizing technology was mainly developed about 80 years ago and started to find application in window frames and cladding in the 1930s. The industry expanded considerably during the 50s and 60s but now relatively little anodized aluminium is used for domestic buildings. However, anodizing is recognized as the most durable finish for aluminium for facades in major architectural projects. Recent examples include the ING House in Amsterdam and "Les Portes d'Arcueil" project in Paris (fig 1).

The purpose of anodizing is to preserve and enhance the natural appearance of the aluminium metal. It produces a thin film on the metal surface, which provides a barrier against corrosion of the aluminium. The film is transparent so does not obscure the aesthetic qualities of the underlying metal, yet is porous at an appropriate stage during production so colorants may be embedded within it. The film comprises a form of alumina, which is resistant to weathering, wear and abrasion.

The aim of this paper is to explain anodizing, and through a description of the properties of anodized aluminium, indicate its importance to architects and designers. In particular, we focus on the technology associated with coloured and textured products, and include new developments and longer term opportunities.

ANODIZING PROCESSES

"Anodizing" is often used to cover all the processes that are carried out by an anodizer in the production of anodized aluminium. There may be more than four main process steps, each of which has a distinct function that contributes to the properties of the final product. Only one of these is truly anodic oxidation. It is convenient to consider each separately but in the sequence of the anodizing production line.

All conventional aluminium alloys may be anodized but the properties of the final products can vary considerably [1]. For instance, alloys containing high levels of copper give rise to defective anodic films that offer reduced corrosion protection compared with purer alloys. In order to achieve good uniformity of appearance from anodizing, aluminium sheet or extrusions have to be produced to particular high standards. Aluminium companies have their own in-house procedures to produce "anodizing quality" products. These are generally based on rather pure aluminium alloys where surface defects, haze or coloured overtones may be avoided. More detail on the importance of the alloy is given below associated with each process step.

Different processes stages in an anodizing line are illustrated in fig. 2. Whereas some metallurgical industries have relied on environmentally-damaging organic solvents to remove grease and oils before surface treatment, this has not been normal practice among anodizers. Semi-fabricated aluminium products are cleaned using aqueous solutions which dissolve or saponify lubricant residues and dissolve bulky surface oxides that are present on magnesium-containing alloys [2].

The function of the second stage in an anodizing line is to prepare the aluminium surface to give the reflectivity and visual uniformity required of the final product. Consequently, it is very important in achieving the appearance required by a designer. It often involves etching the metal using a solution based on sodium hydroxide to generate a matt, metallic appearance. The reaction between the solution and the aluminium surface depends on the different electrochemical properties of the aluminium matrix and intermetallic compounds dispersed within it [3]. An analogy is galvanized steel. There, the zinc coating in contact with the steel substrate dissolves preferentially in aggressive environments because the zinc is more electrochemically basic than the steel; thus it protects the steel. The surface of an aluminium alloy contains many microscopic intermetallic particles such as those formed between aluminium and iron, which are more electrochemically noble than the aluminium matrix. Just as steel drives the dissolution of the zinc coating, these particles drive the dissolution of the aluminium. However, as each particle is so small, its contribution is rather ephemeral before the aluminium dissolves away from it. The result is a surface topography of microscopic, shallow, saucer-like pits about 10µm in diameter (fig 3) which diffusely reflect incident light. Generally the process is designed so sufficient aluminium is dissolved to remove surface irregularities arising from the extrusion or rolling process used to produce the aluminium component.

Etching is a very sensitive process. Reproducible results depend not only on a consistent metallurgical composition and microstructure of the alloy but also a consistent etches solution [4, 5].

Following the etch is immersion in an acidic solution, which dissolves any surface residues (smut) that were insoluble in the sodium hydroxide.

The anodizing process itself is an electrochemical one that oxidizes the aluminium surface in a sulphuric acid solution. The aluminium is the anode in the electrochemical cell. The oxidation process is unique in producing a film with a very regular porous structure (fig 4). The pores are parallel-sided opening at the outer surface of the film and extending perpendicularly almost to the aluminium substrate. They are about 15nm in diameter and occupy about 10% of the volume of the film. The film grows at the metal / oxide interface due to the flow of ionic current passing along the length of the pores under the applied electric field. The thickness of the film is proportional to the amount of electrical charge passed, while the pore structure is determined mainly by the anodizing voltage [7]. Coil anodizing uses current densities about ten times higher than those for batch anodizing, which means that anodic films up to 20µm thick can be produced in a few minutes. Electrical control makes the process easy to run in a reproducible and consistent manner.

As the mechanism of anodizing involves the oxidation of the metal, the film formed is not a deposited coating. It grows out of the metal, is integral with it and therefore is not subject to adhesive failure. In fact it is impossible to separate the anodic film from the aluminium without using rather extreme techniques such as melting the metal. More oxide is produced than the amount of metal consumed. The ratio [8] is constant so, for instance, about 15µm of metal are oxidized to produce 20µm of anodic film. Therefore, the component becomes bigger due to anodizing.

After anodizing, one or more of a number of different processes may be used to introduce colorants into the pores of the anodic film. Colouring processes are described in more detail below. However, the most commonly used are dyeing and electrolytic colouring. The first involves the absorption of a dyestuff into the anodic film from an aqueous solution. The second uses an electrolytic process to deposit metal, generally tin, at the base of the pores of the film, which modifies the reflectance spectrum of the surface.

The final step in an anodizing line is sealing the pores of the anodic film. Generally, water often containing specific additives, is used at temperatures in excess of 96°C. During the process, the anodic film material is hydrated. A re-distribution of mass leads to the pores being filled with a more voluminous hydrous alumina [9]. This seals in any colorants and consequently prevents the bleeding of dyes or leaching of other materials. It also prevents absorption into the film and increases the barrier against corrosion provided by the film. Before sealing, aggressive species have easy access down the pores to attack the aluminium substrate. After sealing, this route is no longer accessible.

Anodizing lines are constructed in different ways. Extrusions, castings, forgings and cut sheet are treated in batch processing lines. The aluminium components are attached to supporting frameworks which are moved in and out of a series of processing tanks using cranes. Coil anodizing lines treat strip before it is cut into sheets. Each coil is unwound at one end of the line, fed through the different processing stages and then rewound at the other end of the line. Batch anodizing lines are more flexible while coil anodizing lines are faster and facilitate closer process control.

PROPERTIES OF ANODIZED ALUMINIUM

This section describes the main properties of coil-anodized aluminium. However, most properties are the same as those found with batch-anodized products. Any distinctions are noted.

As the purpose of anodizing is to preserve and enhance the natural appearance of the aluminium, appearance and weathering resistance are important properties. We can consider two aspects of appearance. One is reflectivity and the other is colour. The reflectivity is mainly determined by treatments before the anodizing process itself. Thus, etching the aluminium creates a surface that reflects light diffusely to produce a “satin” matt appearance. Because, the process involves a reaction between an aqueous solution and the aluminium alloy, the appearance can vary slightly depending on the alloy or its source. This is quite different from a painted surface where the substrate has little effect on the reflectivity.

There is a further difference between anodized aluminium and painted materials. The mechanism of anodizing means that the anodic film replicates the topography of the substrate; the roughness of the etched surface is retained on the surface after anodizing.

Although, the transparency of aluminium oxide enables the appearance to be dominated by the reflectivity of the aluminium, some light is reflected from the surface of the oxide particularly at glancing angles [10]. The property of double reflection from the two rough but duplicate surfaces leads to an interesting optical effect. It gives the illusion of movement as the viewing angle is changed. In contrast, as paint is a deposited coating, it fills depressions in the substrate surface leading to a very smooth topography. Thus, even transparent or metallic paints cannot reproduce the appearance of anodized aluminium.

Colour may be introduced into anodic films using organic or inorganic colorants. Organic ones such as dyes offer a wide range of colours although not as wide as are available with paints. Also, depending on the dye molecules involved, there may be differing susceptibilities to the effect of ultra-violet radiation in sunlight. Some dyes are sufficiently resistant that they may be used with anodized aluminium in outdoor applications with little loss in depth of colour over 10 years [11]. However, others change colour at an unacceptable rate when exposed to sunlight and can only be used safely indoors.

Current processes with inorganic colorants are restricted to those that give ranges of gold and bronze colours. New processes, described below, will extend this to other hues. An important characteristic of these inorganic colorants is that they are resistant to ultra-violet light [11]. This is because they are metallic or simple inorganic compounds that are not degraded on the molecular level as are many of the complex molecules of organic colorants.

If anodized aluminium is properly specified and prepared, it will withstand the effects of weathering for very many years. There are buildings that were constructed in the 1930s still with their original facades including anodized extrusions that are virtually unchanged [12]. Coil-anodized facades in urban environments in Western Europe dating from before 1980 have been surveyed and found to show negligible degradation [13]. Products are supported by a 20-year guarantee regarding appearance, corrosion resistance and durability. In comparison with other metallic materials, anodized aluminium is particularly suitable for marine environments [14].

There are a number of characteristics of anodized aluminium that lead to its good outdoor exposure performance. Unlike organic coatings, anodic film material is impermeable to environmental species. For corrosion of the aluminium metal to take place, the anodic film must be removed or penetrated [15]. Anodic film material is hard, usually more so than glass [16]. This means that wind-born abrasive material as might be found adjacent to sandy beaches erodes the anodized surface only very slowly. Humidity cycling or freeze/thaw processes particularly in the presence of acid pollutants lead to a slow reduction in the thickness of an anodic film [17]. However, service experience has revealed that the thickness loss may be undetectable after 25 years exposure [13].

As described above, the anodic film is not a deposited coating; it is integral with the aluminium substrate. One consequence is that anodized aluminium is not susceptible to filiform corrosion. Filiform corrosion of painted aluminium may occur where the metal surface has been inadequately prepared before the paint application [18]. The corrosion initiates at breaks in the coating or at cut edges and proceeds along the interface between the metal and the coating generating voluminous corrosion product that lifts locally the paint producing the characteristic worm-like features. The correct preparation of the metal surface involves the removal of a thin, active surface-layer produced during rolling or extruding the metal [19]. The layer is normally removed by the etching step in an anodizing line. However, even if etching were omitted, the active layer is sufficiently thin that it would be consumed by oxidation during the anodizing process.

Outdoor exposure leads to the build up of dirt, aerosols and detritus on the surface of materials. These may absorb water and in humid environments may remain moist. If the area is polluted, then acidic species from the atmosphere will dissolve in the moisture and initiate local dissolution of the surface of the material. For this reason regular cleaning is important. Anodized aluminium is no exception. However, if cleaning has not been carried out for many years and encrustations have built up on the surface, anodized aluminium may be readily renovated [20]. The hardness of the anodic film means that mild abrasive materials may be used to remove the encrustations and can restore the surface to its original appearance. This is because the reflectivity of the surface is primarily determined by the condition of the aluminium (beneath the anodic film) which is unaffected by weathering processes.

Life-cycle analyses are an important tool in assessing the sustainability of materials as well as evaluating economic aspects. Aluminium alloys have the advantage of high strength-to-weight ratios. This means that a component designed to have a particular strength will be much lighter than most alternative metals and produce a lower loading during transportation and in structures. Further significant life-cycle benefits arise from the long lifetime of anodized aluminium in outdoor applications [21]. The long life means that more material is being consumed into these applications than is arising from dismantling buildings. Where a building or façade reaches the end of its life, anodized aluminium components can be readily recovered for recycling; the value of aluminium acts as an incentive. The anodic film is fully compatible with aluminium recycling processes [21]. There is no need to employ a decoating operation before loading the scrap into a remelt furnace. Nor is it necessary to use special emission control systems as would be required if the aluminium had a paint coating. The aluminium may be recycled into anodizing quality sheet for reuse in the same applications [21].

The environmental impact of an anodizing plant is relatively low. It does not use organic solvents. There are atmospheric emissions from some of its water-based process solutions but these can be controlled by simple extraction and scrubber systems. Zero-discharge plants are feasible and the worldwide industry is moving in that direction [22].

FABRICATION WITH COIL-ANODIZED ALUMINIUM

Where the surface treatment has been applied correctly, coil-anodized aluminium sheets may be subjected to all normal fabricating processes including slitting, cutting, levelling, machining, bending and forming. A characteristic of coil-anodized aluminium is the presence of fissures within the anodic film, which are produced because the film is less flexible than the metal [23]. However, those arising from operations such as bending and cutting are generally restricted to a narrow region a few millimetres wide at the bend or cut, which appears as a region of slightly different reflectivity. It has been shown that despite the presence of fissures, there was protection against the corrosive attack of the aluminium substrates [23].

COLOUR ANODIZING

Techniques to generate colour

Historically, many processes have been explored or developed for colour anodizing, which depend on a range of principles [24]. Colorants may be introduced into the pores under an electric field or purely relying on diffusion; these are the most frequently used methods. Double decomposition processes which rely on the production of coloured compounds in situ in the pores have been seldom used commercially. When certain alloys are anodized, non-aluminium components from the alloy become incorporated in the anodic film making it coloured. Anodizing electrolytes based on organic acids instead of sulphuric acid impart colour to the anodic film by incorporating particular organic radicals into the film material. These techniques were popular but have now been largely superseded on economic grounds.

The electrolytic deposition of metals at the base of the pores has the advantage that the colorant is well protected by the anodic film and is remote from the external environment. Fig 5 shows the cross-section of an anodic film with tin particles, appearing as white rods, in the pores. The concentration of the deposits is greater at the base of the film near the aluminium substrate but the filling of the pores is quite irregular. This is equivalent to a layer of irregular thickness containing colloidal metal particles, which has a characteristic reflectance spectrum dependant of the deposited metal [25]. In the case of tin, there is greater absorption at the blue end of the visible spectrum so the anodized surface appears bronze. An analogous system is Purple of Cassius, which consists of colloidal gold.

An alternative optical phenomenon, the interference of light, may be exploited to produce a wide range of colours. This will be a new technique for coil anodizing and is described below.

Organic dyes adsorb first onto the film material at the pore mouths and then progressively extend into the pores [11]. Thus, darker colours due to more dye adsorption tend to be more stable than lighter ones. Organic dyeing has been used after electrolytic colouring [26]. An example would be a red dye followed by medium bronze electro-colouring to produce a dark red. As the deposited metal absorbs light preferentially at the blue end of the visible spectrum and extending into the ultraviolet range, it reduces the exposure of the dye to ultraviolet effectively increasing its ultraviolet resistance.

Light-fast gold colours are generated by impregnating the pores with solutions containing ferric ions. Due to local solution conditions in the pores, these precipitate as a coloured, hydrous iron oxide [24]. An example of a double decomposition process is where the pores are initially impregnated with cobalt acetate solution [24]. Subsequent immersion in a solution of sodium sulphide produces a black precipitate of cobalt sulphide in the pores. These colorants tend to be located near to the surface of the anodic film and penetrate further in depth as more colorant is produced, which creates a more intense colour.

So-called integral colouring processes were very popular until the 1970s. Their use of anodizing electrolytes that required high power inputs per unit anodic film thickness and sometimes special aluminium alloys made them expensive. The processes gave grey, brown and yellow colours through to deep bronze and black. The colours are produced by a number of mechanisms which may operate simultaneously [27]. Coloured organic radicals from the anodizing electrolyte have been identified in the anodic film material. Intermetallic particles that anodize more slowly than the aluminium matrix become incorporated in the anodic film where they act as scattering centres for incident light. Alloying elements in solid solution in the aluminium matrix become incorporated into the anodic film material as ions which, in the case of copper, manganese or chromium, have inherent colour. Colour has also been attributed to the presence of non-ionic aluminium in the anodic film. One characteristic of all these mechanisms is that the concentration of colorant in the anodic film increases as the film thickness increases. Consequently, there is less flexibility in selecting colour independently of anodizing conditions than with the other colouring processes.

Current products and new developments

The colours currently available with coil-anodized aluminium include ranges of gold and bronze colours produced using inorganic colorants and both neutral and more saturated hues using organic dyes. Essentially the same ranges are available with batch-anodized extrusions. However, there are limitations particularly when operating sensitive processes. The process tanks in a batch-anodizing line have to be long enough to accommodate standard lengths of extruded sections, deep enough to take an economic load of sections yet as narrow as possible to conserve space[28]; they may be 6m x 2.5m x 0.7m. Such dimensions make it difficult to maintain a uniform solution temperature throughout the tank. This affects heat dissipation from the surfaces of the aluminium components and the uniformity of electric current distribution. The geometry itself puts significant demands on the throwing power of the electrolytic processes. These factors particularly manifest themselves during electrolytic colouring of large cut sheets to produce light bronze colours.

In a coil-anodizing line, forced electrolyte recirculation and the movement of the aluminium strip minimize local heating effects, while the ability to align the counter-electrodes with the strip dimensions ensures good current distribution. Thus, coil anodizing is more controllable, which enables the colour range of sheet products to be extended to include uniform light bronzes.

Coil anodizers are continuing to make advances in process control as the requirements for particular products become more demanding. Also, the market is expecting the range of colours available to be extended still further. Advances will come from a sound scientific and technological base. We have three components in our programme to advance our understanding. The first involves a numerical simulation of the anodizing and electro-colouring processes[6]. Fig 6 shows the potential drop in the aluminium strip as a function of the position along its length through the anodizing and electro-colouring processes. The simulation involved the application of an alternating voltage with a peak value of 30V for electrolytic colouring. The power for electrolytic colouring is introduced to the strip immediately before the anodizing section. This simulation revealed that the ohmic drop in the strip depends on the phase of the electro colouring signal and that electro-colouring occurs with a non-constant voltage bias. These affect the rate of electro-colouring. Such simulations enable us to predict how hypothetical modifications to the anodizing line or electrolytic cells will influence critical process variables such as current density.

The second aspect focuses on the relationship between process variables and the microstructure of the coloured anodic film. As indicated above, the development of the structure of an anodic film is well understood, but there are deficiencies in the understanding of metal electro-deposition during colouring and the effect of the anodic film structure. Fundamental understanding has progressed little since the work of Thorne et al. twenty years ago[29].

The third component aims to produce an optical model relating microstructure of the coloured film to perceived colour. We have used the CIE 1976 (L* a* b*) system[30] to plot in L* b* colour space the co-ordinates of a full range of bronze colours produced by coil anodizing with electrolytic colouring in a tin-base solution. A second order polynomial trend line was fitted to the data with a high level of correlation (fig 7). However, without an appropriate model, we do not understand the physical significance of this finding.

If these new developments are successful, we will have a capability to define a process to produce a particular colour. In the short term this science-based approach is already providing benefits. A range of light-fast colours extending from a light grey through to a deep black is becoming available.

In the longer term, the optical model will greatly facilitate our development of interference colours. The use of electrolytic colouring to generate colours by optical interference has been referred to above. Previously, such processes have been exploited only to a limited extent and only by a very small number of batch anodizers worldwide. We are embarking on a project to extend and adapt this technology for use on a coil-anodizing line. The technology depends on modifying the anodic film pore structure adjacent to the aluminium substrate and electro-depositing a small amount of metal into that pore structure[31]. This produces a thin layer within the anodic film that has a different dielectric constant. Thus, similarly to thin layers of oil on water, spectral colours can be produced by the interference of light depending on the layer thickness. This differs from the mechanism of colour generation from conventional electrolytic colouring (fig 8). It is anticipated that the interference colours will be subtle, of medium or low intensity and with different degrees of lightness. However, the technology is also capable of quite intense dichroic effects.

ANODIZED ALUMINIUM AND TEXTURE

In addition to colour, coil-anodized aluminium may have other interesting decorative effects integrated into it. These may be broadly described as “texture”. It is difficult to define what is meant by the texture observed on anodized aluminium. Analogies with the textures of fabrics may be too limiting. Texture may imply tactile properties as well as visual appearance. Although the anodic film is too thin to provide a major thermal barrier, it is sufficiently thick that an anodized surface feels slightly warm in contrast to a metallic surface that always feels cold. Also, a sealed anodized surface is non-absorbent. Consequently, it is not marked by fingerprints as are metallic surfaces. Further, the hardness of the surface makes it very resistant to the wear that may be caused by continual manual handling or touching. Otherwise the feel of anodized aluminium depends on the topography developed on the underlying aluminium.

Visual appearance may relate to the roughness of the material. At one extreme, aluminium may be produced with a very smooth topography. This requires the use of particularly smooth steel rolls and special rolling practices at the aluminium mill followed by chemical or electrochemical brightening. The total reflectance of aluminium exceeds that of most other metals so providing it with a smooth, clean surface in this way leads to high specularity[32]. Subsequently, anodizing makes it into a durable mirror. At the other extreme are rough surfaces with deep matt appearances produced by chemical etching or blasting with an abrasive media.

One new product is almost indistinguishable from brushed stainless steel, yet has the benefits associated with anodized aluminium. For lift interiors, these include light weight, resistance to fingerprinting and good cleanability. The finish is achieved by brushing the aluminium surface at the aluminium mill before the coil is sent for anodizing which includes the introduction a controlled, low level of colour into the anodic film.

Aluminium mills have the ability to produce a wide range of other surface effects on aluminium strip by using methods including embossing and rolling the metal with specially prepared steel rolls. A pattern is created in the surface of the roll that mirrors the effect desired on the aluminium surface. Consequently, during cold rolling with such a roll, the pattern is replicated on the aluminium strip. Texture effects include Butler finish, fir tree, linen, rice grain, and stucco, tread plate and perforated (fig 9). Following anodizing, these finishes may find application in partitions, kitchen furniture, appliances and many kinds of hardware sets.

A New Zealand company is transferring designs onto anodized aluminium surfaces for architectural applications[33]. Although it is not clear what technology is being used, it is likely to be some form of printing. Printing patterns, logos, product descriptions or instructions for use is well established for (non-anodized) aluminium rolled products used in beverage cans and foil packaging.

NEW FRONTIERS

New frontiers lead to unfamiliar countries.

Colour-anodized aluminium has been used frequently for artistic purposes. One concept replicates the Japanese tradition of mecum game[34]. It exploits the fact that different aluminium alloys colour differently. The substrate consists of laminated sheets of different alloys, which are subsequently partially ground away to create patterns; anodizing enhances the patterns by intensifying colour differences. Another idea that has been used for jewellery involves the use of thickened dyestuffs and immersion dyeing followed by fracturing the anodic film[35]. The surface has both texture and colour (fig 10). It would be interesting to investigate whether approaches similar to these could be successfully developed on a commercial scale.

Other potential methods might develop surface features of much larger dimension comparable to that of aluminium sheets for external applications. Currently, architects expect anodized aluminium to be perfectly uniform, which is an unnatural state for a natural finish. The possibilities depend on the ingenuity of the engineer, the creativity of the designer and an adventurous customer.

SUMMARY

1. Coil anodizing preserves and enhances the natural appearance of aluminium metal. The life cycle of anodized aluminium reveals a product with good sustainability.

2. In general the science and technology of anodizing is well understood but there are areas, particularly in electrolytic colouring, where further improvement will lead to the development of new products.
3. Coil-anodizing processes are in general inherently more controllable than batch processes, which enables good uniformity of colour and appearance.
4. There are many technological approaches to provide colour and texture for anodized aluminium. These may offer new options for designers in the future.

REFERENCES

1 S.Wernick, R.Pinner & P.G.Sheasby: The surface treatment and finishing of aluminium and its alloys, 5th ed., Finishing Publications Ltd., Teddington, England, 1987, pp. 369-373.
2 A.W.Brace & P.G.Sheasby: The technology of anodizing aluminium, 2nd ed., Technicopy Ltd., Stonehouse, England, 1979, pp. 39-43.
3 E.V.Koroleva, G.E.Thompson, G.Höllrigl & M.Bloeck: Corrosion Sci., 1999, vol. 41, pp. 1475-1495.
4 R.C.Furneaux, B.R.Ellard, S.A.Court & A.Bosland: Benelux Métallurgie, 1997, vol. 37, pp. 85-88.
5 A.W.Brace & P.G.Sheasby: The technology of anodizing aluminium, 2nd ed., Technicopy Ltd., Stonehouse, England, 1979, pp. 44-46.
6 I.De Graeve, G.Nelissen, R.C.Furneaux, B.Van der Linden, J.Deconinck, E.Stijns & H.Terryn, Vrije Universiteit Brussel in: Aluminium Surface Science and Technology, Beaune, France, 14-18 May 2006.
7 J.P.O'Sullivan & G.C.Wood: Proc. Roy. Soc. London, 1970, vol. A317, pp. 511-543.
8 S.J.Garcia-Vergara, L.Iglesias-Rubianes, C.E.Blanco-Pinzon, P.Skeldon, G.E.Thompson & P.Campestrini, University of Manchester in: Aluminium Surface Science and Technology, Beaune, France, 14-18 May 2006.
9 K.Wefers: Aluminium, 1973, vol. 49, pp. 553-561, 622-624.
10 L.Mattsson in: 5th Aluminium Chair, Aluminium for its Functional Surface Properties, Brussels, Belgium, 6 March 2002.
11 C.H.Giles: Trans. Inst. Metal Finishing, 1979, vol. 57, pp. 48-52.
12 B.R.Ellard, Novelis Technology, Neuhausen, Switzerland, private communication, 2004.
13 Coil SA/NV, Landen, Belgium, http://www.coil.be/pdf/applications/Building_Inspection_en.pdf (2005).
14 S.Wernick, R.Pinner & P.G.Sheasby: The surface treatment and finishing of aluminium and its alloys, 5th ed., Finishing Publications Ltd., Teddington, England, 1987, pp. 932-933.
15 R.C.Furneaux, Benelux Métallurgie, 2003, vol. 43, pp. 84-89.
16 V.F.Henley: Anodic Oxidation of Aluminium & Its Alloys, Pergamon Press Ltd., 1982, p. 129.
17 R.C.Furneaux, W.R.Rigby & B.G.Carter: Metals Australasia, 1985, vol. 17, pp. 20-23.
18 R.C.Furneaux, B.R.Ellard & M.P.Amor in: 7th International Aluminum Extrusion Technology Seminar, Chicago IL, 16-19 May 2000, pp. 369-380.
19 G.M.Scamans, A.Afseth, G.E.Thompson & X.Zhou: Benelux Métallurgie, 2000-2001, vols. 40-41, pp. 9-16.
20 S.Wernick, R.Pinner & P.G.Sheasby: The surface treatment and finishing of aluminium and its alloys, 5th ed., Finishing Publications Ltd., Teddington, England, 1987, pp. 546-549.
21 R.C.Furneaux in: A. Keiller & S.Ledbetter (eds.), Proc. Conf. Whole Life Performance of Facades, University of Bath, England, 2001, pp. 159-168.
22 R.C.Furneaux, S.A.Finlayson, N.A.Darby, T.Miyashita, B.R.Ellard & G.C.Holywell: Plating and Surface Finishing, 1995, vol. 82, pp. 88-94.
23 G.Gantois, R.C.Furneaux, I.De Graeve & H.Terryn, Coil SA/NV in: Aluminium Surface Science and Technology, Beaune, France, 14-18 May 2006.

24 S.Wernick, R.Pinner & P.G.Sheasby: The surface treatment and finishing of aluminium and its alloys, 5th ed., Finishing Publications Ltd., Teddington, England, 1987, p. 553.

25 D.G.W.Goad & M.Moskovits: J.Appl.Phys., 1978, vol. 49, pp. 2929-2934.

26 S.Wernick, R.Pinner & P.G.Sheasby: The surface treatment and finishing of aluminium and its alloys, 5th ed., Finishing Publications Ltd., Teddington, England, 1987, pp. 648-652.

27 K.Wefers & W.T.Evans: Plating and Surface Finishing, 1975, Oct., pp. 951-957.

28 A.W.Brace & P.G.Sheasby: The technology of anodizing aluminium, 2nd ed., Technicopy Ltd, Stonehouse, England, 1979, p. 23.

29 N.A.Thorne, G.E.Thompson, R.C.Furneaux & G.C.Wood in: R.S.Alwitt, G.E.Thompson (eds.), Proc. Symp. on Aluminum Surface Treatment Technology, Electrochem. Soc., Pennington NJ, 1986, pp. 274-290.

30 International Commission on Illumination, Vienna, Austria, http://www.cie.co.at/ (2006)

31 P.G.Sheasby, J.Patrie, M.Badia & G.Cheetham: Trans. Inst. Metal Finishing, 1980, vol. 58, pp. 41-47.

32 B.Van der Linden, S.Holten, H.Terryn & E.Stijns: Benelux Métallurgie, 2000-2001, vols. 40-41, pp. 84-88.

33 Aluminium Anodisers Ltd., Auckland, New Zealand, http://www.aalum.co.nz/Supporting/aluart1.html (2004).

34 I.T.Ferguson, Brian Derby & G.E.Thompson: Mater. Res. Soc. Symp. Proc., 2005, vol. 852, pp. OO1.3.1-OO1.3.7.

35 Jane Adam, London, England, http://www.janeadam.com (2006).