Digitalisation of UK Aluminium Anodisation

iAMS Technical Report

Digitalisation of UK Aluminium Anodisation

Technical Report 2021-01

Ché Cameron *(c.cameron@qub.ac.uk)*

John McLoughlin

Pantelis Sopasakis

Seán McLoone *(s.mcloone@qub.ac.uk)*

Cite as:

Cameron, C. (2021): "Digitalisation of UK Aluminium Anodisation", Technical Report 2021-01, Centre for intelligent Autonomous Manufacturing Systems, Queen's University Belfast

Acknowledgements

The insights and experience shared by commercial aluminium anodisers were essential in creating this report. The authors would like to thank Dean Harding (Snelsons), Tom Mallon and Nigel Bell (RLC Langford), Jonathan Buckley (Colour Anodising) and our other industrial partners for their time and valuable input.

About iAMS, Queen's University Belfast

The Centre for intelligent Autonomous Manufacturing Systems (iAMS) purpose is to research, develop and demonstrate innovative technologies that enable and underpin the rapidly evolving digital manufacturing world. It is composed of an interdisciplinary team of researchers spanning the disciplines of Engineering, Computer Science, Mathematics, Statistics, and Psychology working in partnership with the Northern Ireland Technology Centre to develop innovative technologies and solutions that address the challenges of Industry 4.0.

About the DSM Network

The Digitalised Surface Manufacturing (DSM) Network aims to capture and understand the current UK coating research and manufacturing framework and pump-prime digitalisation activity to move the sector forward towards Industry 4.0.

The DSM Network is a £1M investment by the EPSRC to bring together the diverse expertise and capabilities in UK academia to enhance digitalisation in the surface manufacturing sector. The group is made up of members from The University of Manchester, Queen's University Belfast, The University of Sheffield and London South Bank University.

Executive Summary

This feasibility study into the digitalisation of the aluminium anodisation process was undertaken by members of the EPSRC Digitalised Surface Manufacturing (DSM) Network+ group which aims to capture and understand the current UK coating research and manufacturing framework. The work was carried out by the Centre for intelligent Autonomous Manufacturing (iAMS) at Queen's University Belfast whose purpose is to research, develop and demonstrate innovative technologies that enable and underpin the rapidly evolving digital manufacturing world.

Aluminium Anodisation is a long-estabished industrial process that is generally well understood and competently operated in the commercial world. Due to the off-shoring of manufacture, British Anodisation companies will generally compete in niche markets and through providing consistently high quality work on difficult and short run jobs.

The type of work undertaken by anodisers in Britain is generally resistant to automation and relies upon a significant human labour input (loading/unloading, transport and inspection of parts). Quality is achieved through disciplined working practices that have been refined through experience and this paradigm must be respected through the journey of digital transformation.

Issues arising after anodisation are generally caused by preceding steps and usually cannot be compensated for by the process itself. Defects result in rework or spoilage and the prevention of such problems relies upon refined procedures and careful handling/inspection of parts.

There is not a widespread pressing demand for fundamental research due to the maturity of the process. Research and innovation work would be best focused upon developing in-situ sensors, building process parameter development tools and generalising process models to create positive impact in the industry.

Pressure from environmental regulations may provide an additional stimulus to research, innovation and industry players. The transition from established chemical make-ups will cause disruption that could be greatly eased by a functional digitalisation system.

Digitalisation effort should focus upon in-situ sensing of anodic film thickness (several potentially cost-effective technologies have been repeatedly proven in lab settings) and implementing parts traceability systems for issue identification and prediction. These systems could reduce operator workload, improve consistency and increase the responsiveness of anodisation companies by enabling them to adapt to variations in job or material specifications without disrupting known-good procedures.

Contents

1 Introduction

This technical report examines the feasibility and demand for Digitalisation Technology in the commercial Aluminium Anodisation sector with respect to the needs and challenges of commercial anodisers in the UK. The original focus of a data-driven case study in partnership with an aerospace manufacturer was modified in response to disruptions caused by Covid-19.

Funding was provided by the EPSRC Digitalised Surface Manufacturing (DSM) Network+ group as part of a £1M investment by the EPSRC to bring together the diverse expertise and capabilities in UK academia to enhance digitalisation in the surface manufacturing sector.

The study was conducted in Queen's University Belfast at the Centre for intelligent Autonomous Manufacturing (iAMS). The group is composed of an interdisciplinary team of researchers spanning the disciplines of Engineering, Computer Science, Mathematics, Statistics, and Psychology working in partnership with the Northern Ireland Technology Centre to develop innovative technologies and solutions that address the challenges of Industry 4.0.

This work is informed through review of publicly available research literature and engagement with a selection of commercial anodisation providers representing a variety of sectors in the UK and Northern Ireland. The companies involved completed a survey and shared their experiences via telephone interview.

Section 2 gives a brief overview of the aluminium anodisation process in terms of its electrochemistry and a generic procedure for carrying out practical anodisation work. **Section 3** completes the context by delivering an overview of commercial anodisation activity in the UK, including the major forms of anodisation, common ancillary processes, testing procedures and the structure of trade business.

Common challenges of anodisation operators are reported in **Section 4** and these are used to inform the priorities of the Digitalisation strategy. Contemporary and historic scientific research into aluminium anodisation is reviewed in **Section 5**.

The Digitalisation vision and strategy is laid out in **Section 6**, including a template for digitalisation and the presentation of a phased approach to system integration. **Section 7** summarises the report then recommends areas for research and innovation work to support the digital transformation of the UK anodisation industry.

2 The Aluminium Anodisation Process

Anodisation is an electrochemical reaction (electrolytic passivation) which forms, or thickens, a non-conductive oxide coating on the surface of a metal. The piece to be coated is submersed in an electrolyte and connected as the anode (+ve electrode) of a DC electrical circuit. The current causes release of hydrogen at the cathode (-ve electrode) and oxygen at the anode - growing the aluminium oxide layer.

The reaction is governed by current density but the oxide layer is non-conductive. This introduces a dynamic between applied voltage and current density. As the oxide coating is formed, an acid electrolyte will slowly dissolve the oxidised material. This results in two distinct layers - a solid oxide barrier layer, and a porous oxide layer. The shape, structure and thickness of the porous layer has a direct effect on the properties of the anodised surface. Non-acidic electrolytes will produce a single solid barrier layer.

2.1: Aluminium Anodic Oxide Film

2.1.1 Electrochemical Reaction

An electrochemical cell does work on a chemical system by driving an electrical current through it. It is composed of two half-cells, defined by the reactions at the anode (+ve) and cathode (-ve). The externally applied potential difference forces electrons to flow from cathode to anode, driving a non-spontaneous redox reaction (that may otherwise not occur in stable materials).

The anode undergoes oxidisation and the cathode undergoes a reduction reaction. The electrical current causes the electrolyte to decompose, producing ions that migrate to anode or cathode.

Current in the electrochemical cell causes the acid electrolyte to decompose into Hydrogen and Oxygen ions. The Hydrogen ions migrate towards the cathode and are reduced to Hydrogen gas. Negatively charged ions move towards the anode. The current in the circuit causes the aluminium anode to generate positively charged aluminium ions, resulting in the following oxidisation process:

$$Al \rightarrow Al^{3+} + 3e^-$$

$$2Al^{3+} + 3O^{2-} \rightarrow Al_2O_3$$

$$2Al^{3+} + 3OH^- \rightarrow Al_2O_3 + 6H^+ + 6e^-$$

When the oxide is soluble in the electrolyte, the electrochemical action becomes more complex. Al^{3+} ions are lost into the electrolyte, reducing the efficiency of the process from almost 100% (for a single solid barrier layer) to around 60% (during porous layer formation). This dissolution action is what allows for a thicker, porous layer to form - which is the required surface for bonding, dyeing and painting.

2.1.2 Solid Layer (or Barrier Layer)

The barrier layer is formed at the start of the anodisation process and then stays at a constant thickness for the remaining duration of the process. Increased applied potential during the barrier layer formation leads to thicker anodic films with thicker barrier layers.

The thickness of the barrier layer is proportional to its formation voltage. The following rates are considered almost universal: 1.3-1.4nm/V for single solid barrier layers and 1.2nm/V for barrier layers at the base of porous layers.

2.1.3 Porous Layer

The porous layer is a regularly arranged structure composed of cells, each of which has a central pore that runs perpendicular from the barrier layer and spans to the surface of the porous layer. The pore morphology (width, spacing and depth of pore structure) is affected by the process parameters and the particular aluminium alloy being anodised. Higher applied potential during layer formation results in larger pore cells and wider pores.

Oxide growth takes place at the oxide/metal interface - the outermost layer of oxide is under acidic attack for the duration of the anodisation process. Significant chemical attack can cause the pores to lose structural integrity and collapse. This defect is known as Chalking and it is visually identifiable as a slightly white-coloured powdery film with the properties of reduced hardness and lower adhesion.

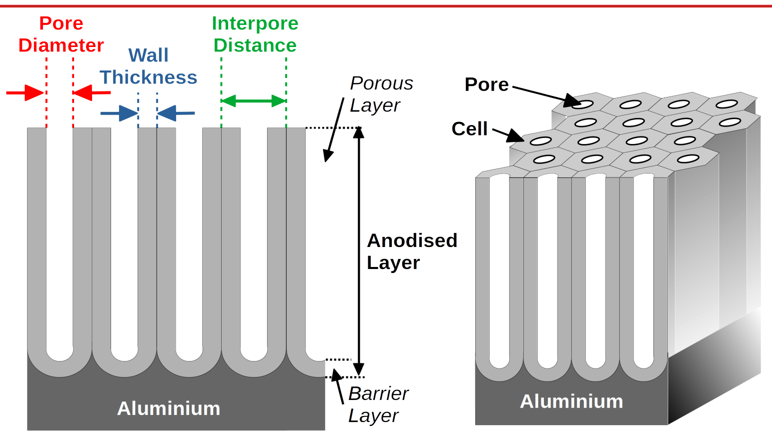


Figure 1: Oxide Structure

Alloying elements can alter the properties of the layer, causing irregular pores with lateral orientation. Alloy incorporations in the oxide can also cause defects. High electrolyte temperature causes pore widening close at the oxide/electrolyte interface due to the higher aggressiveness of acidic dissolution but this effect is decreased towards the barrier layer.

The mechanism of steady state balance between growth and dissolution is not yet completely settled, however the dynamics have been characterised. There is ongoing research activity regarding the formation mechanism, structure and morphology of this porous layer (mostly focused upon its nano-material qualities).

2.1.4 Generic Procedure

The practice of anodising aluminium is characterised by detailed processes and procedures - the following account only serves to familiarise the reader with a generalised view of the anodisation process. Whilst several of these steps are not strictly the electrochemical anodisation reaction itself, these are the bare essential steps in achieving a suitable anodised finish.

Figure 2: Metal Finishes

Polishing / Finishing

Anodisation does put a surface coating on metal however it does not change the roughness of the surface finish at a macroscopic level. The final surface texture (milled, brushed, mirror-polished etc.) must be in place before the anodisation process. Therefore all parts are brought to final-finish before anodisation and then thoroughly cleaned of grease and any other deposits.

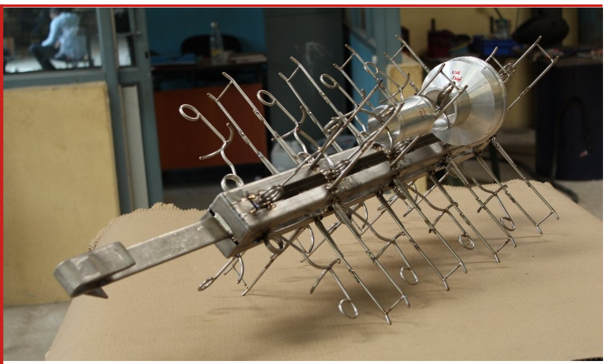


Figure 3: Parts Jig

Loading / Jigging of Parts

Good quality electrical contact is essential for the anodisation process. When treating multiple parts these should all have equivalent low resistance contacts to the carrying apparatus (jig) to ensure consistent treatment across a batch.

Each piece to be anodised is loaded into a jig - this process is difficult to automate unless very similar pieces are to be anodised on a large scale.

Cleaning / Etching

The surface of the part should be 'bare metal' before entering the anodisation tank, so any oxide layer that has formed naturally during storage/transport must be stripped off. Any contaminants on the surface of parts to be anodised will compromise the finish and potentially introduce impurities into the electrolyte solution - degrading the quality of proceeding jobs. Parts should be thoroughly rinsed and inspected as 'clean' before progressing to anodisation.

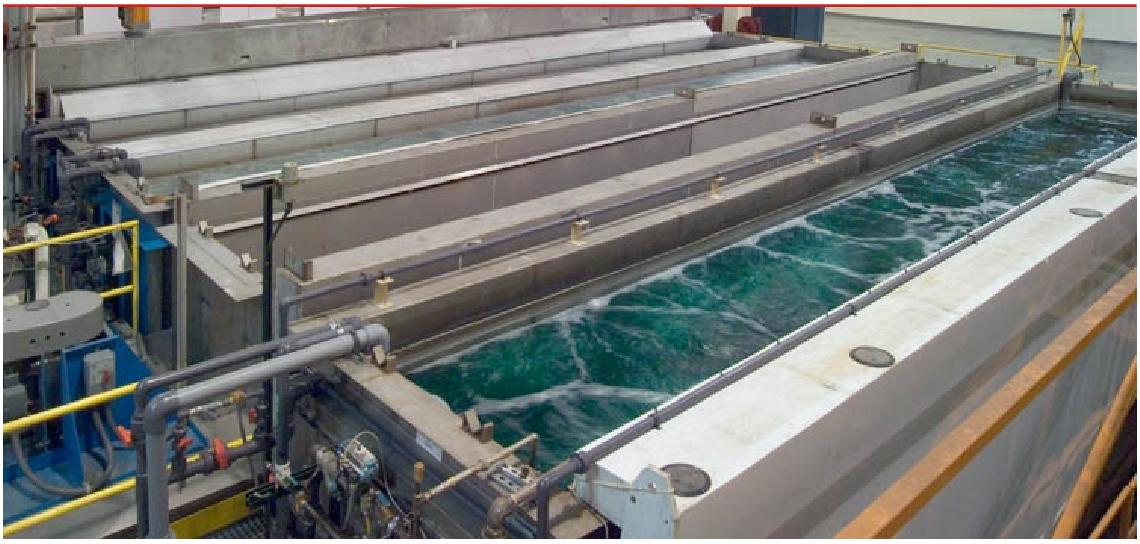


Figure 4: Anodisation Tanks

Anodisation

The jigged pieces are lowered into the anodisation tank which is filled with an electrolyte suitable for the process. Voltage is applied between the cathode (usually plate electrodes affixed to the side of the tank) and the anode (the jig holding the pieces to be anodised). This voltage is applied in two stages: ramp-up and dwell.

During the ramp-up phase, the solid layer is formed. At the beginning of the process, the electrical circuit will have a very low resistance (due to the absence of any non-conductive oxide film on the parts) which is why the voltage must be slowly increased to avoid the current density becoming too high.

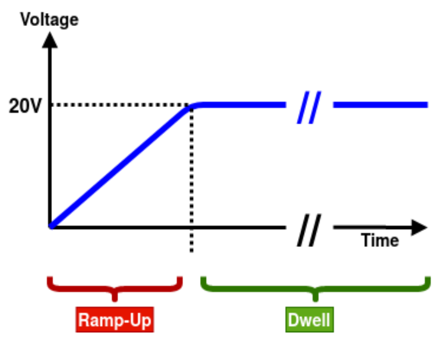


Figure 5: Typical Voltage Profile

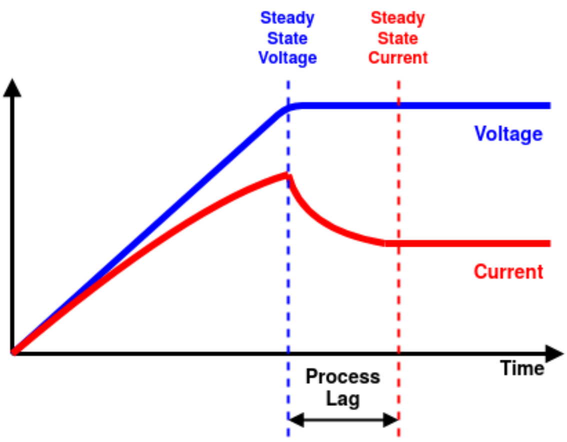


Figure 6: Dynamic lag between Voltage and Current

After the solid layer has been formed, the porous layer is grown during the dwell phase. In this phase, the voltage is held constant and the current density will stabilise at a steady state (with a certain time lag). The final anodic film thickness is proportional to the time spent at this dwell stage.

The process is usually potentiostatically controlled (voltage controlled) because the anodisation process rate is predicated on current density rather than absolute current. Unless the exact surface area of the job and the cathodes is known it is not possible to calculate the appropriate current to produce a given current density. Potentiostatically controlled anodisation therefore has a form of self-regulation wherein a job with pieces that present a large surface area will draw more current, and jobs with a smaller surface area will draw less current - but the current density profile will remain consistent for the same voltage profile.

Sealing / Dyeing

After anodisation the open pores on the part should be sealed. In the simple case this is achieved by submersing the part into heated de-ionised water which hydrates the aluminium oxide to form aluminium hydroxide. If a coloured finish is desired, the part will instead be submerged in a tank containing a dye solution, with the porous structure taking up the dye and retaining the colour. For conversion coatings (parts that will be painted or glued) the pores may be left open to increase adhesion.

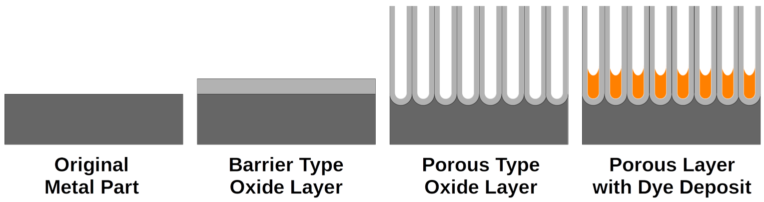


Figure 7: Dyeing of Anodised Parts

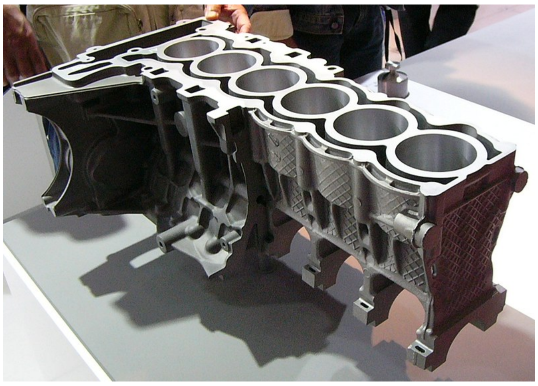
3 Commercial Aluminium Anodisation

Commercial aluminium anodisation is generally operated by maintaining tight tolerances on tank conditions and equipment, then accurately following a defined procedure to produce consistent results. A large selection of publicly available standards documents exist which describe the steps and specifications of standard anodisation processes.

The anodisation standards documents alone are not sufficient to create a viable commercial operation. Working practices must be developed and refined, knowledge and experience in the process must be built and only then will consistent and high quality output be realised.

3.1: Overview

3.1.1 Applications



Aluminium anodisation can cater to a wide variety of applications through modification of the properties of the anodic film. Hard films provide excellent corrosion protection, softer porous films are excellent for glue and paint adhesion. The film structure can be created to be abrasion resistant or to take up dye colours for cosmetic applications.

Adjustment of the anodic film's thickness, ductility and colour, mixture of process additives and choice of aluminium alloy enable a high degree of customisation - choosing these parameters and reaching the desired properties of any given part takes expert knowledge and experience, or, experimentation (and in the case of new parts or processes - almost always both).

3.1.2 Sectors

Many sectors make use of anodisation as a surface finish, each of which has their own requirements. Aerospace uses the anodised finish for conversion coatings to increase adherence of paint and glues or as a final finish for corrosion protection. Automotive and Motorsport can create lightweight parts from aluminium alloys due to the high abrasion resistance and geometric accuracy attainable with the hard anodisation process.

Food and Medical equipment manufacturers favour anodised aluminium due to its ability to be finely finished, thoroughly sealed and go on to provide a long service life in the face of regular contact with oxidising substances and cleaners. Similarly, the sectors of Construction, Power, Oil and Gas make use of the corrosion resistance properties of anodised aluminium.

The Architectural field makes use of special treatments to create finished metals with long-lasting colour fastness and long-term corrosion resistance in service. Cosmetic coloured anodisation is commonly seen in consumer goods - familiar to most readers will likely be the ubiquitous carabiner, often to be seen brightly coloured and hanging from a set of keyrings.

Most sectors will have certain standards and certifications that must be attained by companies that wish to become suppliers. These standards involve not just the anodisation process specifications and the quality of the product that is produced, they also cover internal procedures and record keeping.

3.1.3 Job Specification

The important qualities of the anodised finish are: Thickness, Hardness, Adherence and Corrosion Resistance. The pore morphology directly affects these properties however it is very rarely specified or measured (unless nano-material applications are under consideration). Additives, sealing treatments and process parameters will also affect the structure of the final film - again this is usually not considered in terms of the structural parameters but rather the measured properties of the film in regards to the intended application and job specification.

Anodisation jobs can also be specified using the exact process parameters (voltage profile, dwell times, rinsing processes, chemical make-ups, transportation and handling procedures etc.) however this level of customer control is generally the domain of the Aerospace, Automotive and Defence sectors.

There are several ways in which anodisation trade tends to arise:

- **In-House** services to meet the internal demand for anodisation.
- **Direct Sales** to customers that require anodisation services.
- **Sub-Contracting** from one anodisation or metal finishing provider to another.
- **Hosted Process** where a large customer approaches an existing firm to set up a dedicated line.

In-House services are self-driven in their specifications and will almost certainly develop their own processes to achieve the desired results. If the business produces a consistent range of parts and finishes then these refined processes may become extremely stable and well-tuned - however this may compromise the building of skills to develop and refine new processes in the face of change.

Direct Sale customers will include a spectrum of knowledge and experience from customers who just need a good-looking finish put on a product, to customers that will specify a particular film thickness and porous structure. The anodisation provider will work with the customer specification and that interaction ranges from: recommending the alloy and anodisation process to be used; developing new processes to meet a demanding set of requirements; sending samples to external labs for verification and validation.

Sub-Contract of anodisation work may be due to capacity issues, breakdowns or specialist requirements - in this scenario the specification is normally the final properties of the anodic film, and in rarer cases the parameters of the actual process that must be followed.

Hosted Process requires a close relationship between anodisation operator and customer. The customer will have clear requirements on the parts bring produced and the process parameters that should be used to treat them. The anodisation provider will provide premises, logistics, infrastructure and possibly labour to run the line once it has been set up. This arrangement is more likely to be found near large-scale factories that assemble globally sourced parts (eg. car manufacturers) where the economy of local treatment is realised through volume or through decreased requirements in international shipping/handling of the non-finished parts.

3.2: Anodisation Processes

3.2.1 Type I: Chromic Acid Anodisation

Type I anodisation is the oldest established process, patented in England by Bengough and Stuart in 1923. It is still used today in the aerospace industry and follows a voltage profile ramped from 10V up to 40-50V, followed by a dwell time at the higher voltage. Chromic acid anodisation can produce a film thickness of up to 5µm.

It produces a hard film of self-limiting thickness due to its structure of overlapping plates rather than regular pores. This type of anodisation creates an extremely hard-wearing surface and it is possible to treat multiple alloys simultaneously because of the self-limiting nature of the anodic film growth.

3.2.2 Type II: Technical Anodising (Cosmetic)

Type II anodisation produces a film with a regular geometric porous structure which can be ordered down to the nanoscale. This process typically uses a sulphuric acid electrolyte and is performed at ambient temperature (20°C - 25°C). Typical film thickness ranges from 8-20µm.

The anodic film readily uptakes dye, can be screen printed and creates a corrosion resistant barrier however it does not offer significant abrasion protection. The clarity and brightness of parts treated with the Type II process is unmatched by other anodisation processes, in part due to the optical transparency of the anodic film.

3.2.3 Type III: Hard Anodisation

Type III anodisation is suitable for applications which require a hard coating with high abrasion resistance. A variety of acids and mixtures are suitable as electrolytes although sulphuric acid is most commonly used. The normal range of film thickness is 25-50µm but it is possible to grow films of over 100µm thickness in the correct conditions.

The current density required to grow very thick films must be relatively high and this can cause issues with localised heating and aggressive acidic attack of the anodic film which compromises its structure. This process is carried out in chilled tanks with a temperature ranging from 0°C - 10°C to mitigate against overheating of the solution and parts,

Some anodisation companies will not use chilled vats to perform this type of anodisation but instead use additives to achieve a similar result at ambient temperatures. There is some disagreement in the industry about whether these approaches can be considered as equivalent processes.

3.2.4 Conversion Coatings

Conversion coatings are so named because they assist in the transition from one material to another. The porous structure of the anodic film can be exposed to additives that are adsorbed into its structure. The chemically bonded molecules then act as a primer for an additional coating of paint or adhesive. There is a wide range of specialist formulations that can be used because the additives do not intrude into the aluminium substrate but rather bond to the external oxide structure.

3.2.5 'Electrolytic' Anodisation (eg. Anolok™)

Architectural applications require long-term light-fastness of colour which is currently not possible when using dyes to colourise parts. Electrolytic deposit of metal into the porous surface structure can create colour via the phenomenon of light scattering and produce stable colourised materials.

This process is referred to in the industry as "electrolytic anodisation" and the most well known variant is the Anolok process (licensed by United Anodisers in the UK and originally developed in Japan by Alcan International) which deposits cobalt metal into the aluminium substrate to produce shades varying from light bronze through to black[1].

3.3: Ancillary Processes

Anodisation is not a standalone process and it is generally not possible to compensate for poor quality input materials. The processes before and after the anodisation procedure must be well regulated and operated with discipline. Each successful anodisation operator will have spent significant time and effort on refining their working practices to achieve consistently good results.

The following notes are relevant to all anodisers, however those companies that offer a wider range of services will likely have additional considerations. Companies that operate metal finishing processes which are more demanding of cleanliness than anodisation (eg. electrochroming) will generally benefit from the working practices that they have developed to support the more difficult process.

If processes and logistics are under good control, then taking stewardship of the product from an earlier stage can have significant benefits in terms of ensuring the quality of materials and preventing contamination by unknown substances.

3.3.1 Storage & Handling

Storage of materials should be carefully considered in terms of stresses and contact with foreign substances. Clean storage is essential (or if not clean, then only with known and clean-able contaminants present) and there should be no opportunity for corrosive substances to attack the metal. Acid-free paper where parts are stacked and in contact will also prevent marking from occurring. Larger and heavy parts should be suitably supported because stresses induced in the metal may become visible after anodisation.

Handling of components throughout should reflect the same considerations as storage by avoiding damage through introducing stresses and preventing contamination from occurring. A common consideration is taking care to use clean gloves when handling the materials - fingerprints appearing in the anodised finish is something that all operators have encountered at some point during their careers!

3.3.2 Polishing / Finishing

Anodisation will not cover up surface defects on parts - in fact, it will tend to do the opposite and make them more apparent. Therefore parts must be at final-finish surface smoothness before anodisation. If this finish has been achieved before anodisation then the transport and storage logistics must be well refined to avoid marking the parts.

An alternative is for the anodisation operator to provide polishing services, however a mechanical polishing process introduces contaminants to the site that will require disciplined working practices to avoid compromise of the anodising area. When Chemical Brightening is offered alongside anodisation services, it integrates well with the chemical management and tank-based operations expertise that are already available - however it is not suitable for all aluminium alloys.

3.3.3 Cleaning / Rinsing

Parts must be fully cleaned and degreased before entering the anodisation line (which is itself, often referred to as a 'clean line'). Depending on the level of vertical integration in the company undertaking the anodisation, the cleaning processes may be extensive or they may rely upon parts arriving relatively clean from their customers.

Knowledge of the particular contaminants present on the parts is important for thorough cleaning and to avoid contamination of the chemical and rinsing tanks - this depth of detail is ideally down to the specific machine oils used during fabrication of the parts. Once parts are jigged they will be rinsed several times throughout the anodisation process and it is important to monitor the purity of the rinse tanks to avoid cross-contamination.

3.4: Testing Procedures

The specification, testing and validation of anodic coatings is described in a variety of standards (eg. BS 6161 *"Methods of test for anodic oxidation coatings on aluminium and its alloys"*, ISO 7599:2010 *"Anodizing of aluminium and its alloys - General specifications for anodic oxidation* *coatings on aluminium"*). It is common-practice for companies to develop their own internal standards and testing procedures that are focused upon specific-purpose anodic film performance.

The multi-national nature of modern manufacturing work means that anodisation companies are expected to meet a variety of standards that are relevant to their customers, although these are usually a subset that represent the priorities of that particular customer and job. Conversely, more casual anodisation work (eg. for short-run / one-off cosmetic items) may not be carried out according to any particular standard and will be verified with direct reference to the customer's requirements. In this case the testing procedures and anodisation process is generally still informed by the standards, if not explicitly bound by them.

A brief account of how the primary qualities of interest (thickness, corrosion resistance, hardness and adhesion) are tested is presented in this section. Further details are available through consultation of the relevant standards documents however it must be stressed that each company will have developed their own particular testing procedures that should be considered on an individual basis.

3.4.1 Film Thickness Measurement

Anodisation thickness is typically measured on-site using a non-destructive probe that works on the principle of eddy currents. The probe emits a high frequency magnetic field which induces eddy currents in the aluminium substrate. The induced magnetic field directly opposes the emitted field which causes a measurable signal attenuation. The extent of this attenuation corresponds to the distance between the probe and the conductive metal - which in this case is equal to the thickness of the non-conductive anodic film. This measurement technique is not suitable for submersion in the anodisation electrolyte, must be carried out offline and, requires calibrated instruments.

Other techniques for thickness measurement are optical in nature, leveraging the reflectivity of the aluminium and the opacity of the oxide. It may be possible to integrate optical technology for online measurement during film formation. Detailed inspection of the anodic film is generally via Scanning Electron Microscope (SEM) imagery which can be used to explore porous structure and micro-defects.

3.4.2 Corrosion Testing

Figure 8: Controlled Salt Spray Chamber

Corrosion resistance testing is usually accomplished by means of a salt spray chamber which recreates a harsh corrosive environment. Widely accepted standards for testing apparatus, procedure and interpretation of results are available (eg. *ANSI ASTM B117-19*) and companies with demanding applications may develop their own particular specifications for corrosion resistance.

Providers of anodisation services that regularly produce critical parts (Aerospace, Defence, Automotive sectors) are more likely to have in-house corrosion testing facilities. Other anodisers may use external labs to spot-check their products, assuming that if their process procedures and operating conditions are being correctly maintained that the performance of their products will be consistent.

3.4.3 Hardness Testing

The aluminium anodic oxide is brittle so its hardness is measured using micro-hardness testing. In this technique a diamond probe is used to make an indent on the surface. This probe is applied with a known force and the depth of the indentation is measured to characterise the hardness of the surface under test.

3.4.4 Adhesion Testing

The goal of adhesion testing is to verify the bonds between the substrate, the anodic oxide and a coating which has been applied to it (typically paint). The anodised piece is coated with the desired finish and allowed to cure. The cured finish has a piece of tape firmly applied to it and then this tape is peeled off. If the peeling of the tape delaminates the layers then a failure is recorded. Delamination can occur at the boundary between substrate and oxide, between oxide and conversion/primer, or between primer and surface finish.

4 Challenges in Aluminium Anodisation

In an idealised world; tank chemistry, electrical parameters, material specification and process procedure are refined and perfectly consistent - and in this scenario, the anodisation treatment will be perfect in every case.

Generally speaking, commercial anodisation companies strive to achieve this ideal process through disciplined working practices and by applying lessons learned through previous experience. However there are many factors beyond their control (rendering them unable to create the perfect environment), and most operators of the process will not be repeating an exactly similar job for every anodisation run (leaving the development of the perfect process procedure for every single job an infeasible, or at least commercially unwise, goal).

This situation necessitates an imperfect process which in the worst case produces defective parts and, in the best case defines an allowable envelope of parameters and working practices that result in a viable anodisation operation. The following sections will examine several specific challenges of operating an aluminium anodisation line and recount the conventional mitigations/solutions where they exist.

4.1: Recognised Defects

There are a range of defects which are commonly recognised in the aluminium anodisation process, with a wide variety of proximal causes. It is out of scope of this report to examine these factors in detail, however the excellent work of Ted Short, *"Identification and Prevention of Defects on Anodized Aluminium Parts"*, is widely regarded as a valuable resource within the industry.

4.1.1 Pitting

Pitting can be difficult to troubleshoot because it can occur before, during or after the anodisation process. It can be caused by environmental contamination, improper handling (fingerprint marks from oils on the hand), indelicate transport (where pieces are allowed to rub against one another during transit), acid/alkali attack, contaminations in the rinsing processes and, galvanic corrosion due to metallic impurities or dissimilar metal contact in service.

Figure 9: Defect - Pitting

4.1.2 Streaking

Streaking is observed as a difference in the reflectivity / brightness of the finished part and is caused by a non-uniform material response to etching and anodisation. This variation in response can be due to non-uniform metallurgical structure (stresses in the metal, inclusions in the alloys, variations in the metal grain structure, weld filler material etc.) and impurities introduced by mechanical manufacturing processes.

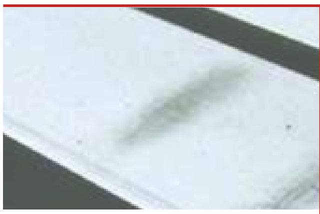


Figure 10: Defect - Streaking

4.1.3 'Burning' during Anodisation

Burning is a discolouration that is caused by localised dissolution of the anodic film. This is generally caused by applying a current density that is too high, causing overheating at weak points in the film. It can be mitigated by use of appropriate voltage profiles and sufficient tank agitation.

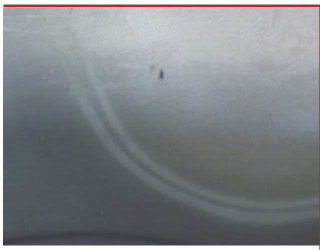


Figure 11: Defect - Burning

Figure 12: Defect - Chalking

4.1.4 'Chalking' after Anodisation

Chalking is the formation of a white deposit on the anodised surface that is caused by the loss of structural integrity of the anodic film. This can arise when the anodic film is too soft (commonly caused by low current density) and/or has undergone structural degradation due to acidic attack (exacerbated by long anodisation times and high electrolyte temperature).

4.2: Film Thickness Control

The anodic film thickness is a critical property of the finished part which is affected by the electrolyte temperature and pH, the anodisation voltage profile (and therefore the current density experienced by the material during the process) and, the particular alloy being anodised along with any additives. Generally the combination of these variables is tuned over time, and the recipe for certain materials and jobs become set procedures - however this does not guarantee absolute consistency.

It is standard practice to include a test piece within a batch which is removed prematurely and has the thickness of its anodic film measured. This measurement is used to calculate a nominal film growth rate for that piece and the assumption is made that all remaining parts have the same film thickness and growth rate - thereby allowing the operator to adjust the remaining dwell time of the batch to produce the correct anodic film thickness.

In cases that the test piece is already at the correct thickness, the process is stopped immediately. When the coating of the test piece is already of a higher thickness than the maximum allowed tolerance then it is likely that the whole batch must either be discarded, or stripped and re-anodised.

When operators must oversee multiple tanks running in parallel it can be challenging to test the film thickness in a timely manner and to manage the correct dwell time of the different jobs - especially in the case of a heterogeneous set of pieces to anodise.

4.3: Anodisation Tank Conditions

There are several factors that must be controlled in an anodisation tank - electrolyte solution concentration, temperature and agitation.

4.3.1 Electrolyte Solutions

Each different anodisation process (as well as the ancillary rinses and dyes) will have a nominal electrolyte and additive concentration. These parameters will also have an allowable envelope, sometimes defined in an industry standard (eg. *AMS 03-25, MIL-A-8625 Type II anodisation*) or locally defined and arrived at through process refinement and experience.

Electrolyte concentration is tested on a regular basis, and is generally adjusted on a weekly schedule (operators of demanding processes or with high utilisation may perform daily adjustments to maintain tolerances). Usually the management of tank solution is provisioned by in-house testing facilities but some operators choose to partner with external chemical companies to maintain their tanks.

Auto-dosing systems exist but are prohibitively expensive for manual low-volume lines - this is because they replace only an aspect of the many required maintenance procedures and do not tend to meaningfully impact the workload of the staff operating a manual or semi-automatic anodisation facility.

4.3.2 Temperature

Tank temperature has a dramatic effect upon the speed and quality of anodisation. There may be a requirement for chilled or heated operation. In the case of chilled operation (for traditional Hard Anodisation) the demands upon cooling infrastructure can be significant - the temperature of the bath should be around 0°C and this must be maintained in the face of resistive heating from the electrical current passing through the electrolyte.

Some operators may carry out anodisation at ambient temperature, however this introduces significant variation into the process. Film thickness can be relatively easily controlled for through the use of a test piece, however the temperature of the electrolyte affects not only the growth rate of the film, it also affects its properties and pore morphology - which are not simple to measure or account for.

4.3.3 Agitation

Tank solutions must be agitated during anodisation for three main reasons: to displace evolved gas on the surface of the parts, to prevent localised heating from the anodisation reaction and, to mitigate localised electrolyte concentration changes. Agitation systems may be air-based (in which case parts must be carefully loaded to avoid air becoming trapped) or mechanically-based.

Insufficient agitation of the tank or improper loading of parts can cause 'airlocks' where a gas bubble becomes trapped against the geometry of the part being anodised thus preventing the formation of anodic film in this area. Overly aggressive agitation may cause parts to become dislodged from their carriers/jigs.

4.4: Chemical Management

A full anodisation line requires etching, rinsing, anodisation and sealing processes - it is also not uncommon to incorporate some form of polishing and more aggressive cleaning (eg. for oils left on parts). This line of processes must be chemically compatible with one another to avoid introducing contaminants that will compromise the output of the production line or the lifetime of the solutions at each stage.

This did not present a significant barrier to entry for smaller operations when environmental regulations were less stringent. As regulatory requirements have increased it has become more expensive to manage and dispose of harmful chemicals, leading to increased operational costs and the requirement for additional documentation and procedures.

Operating well-established anodisation processes affords companies a wide choice of chemical suppliers with the associated price-competitiveness of that scenario. There is a growing demand for more environmentally friendly processes (moving away from Chromate based electrolytes) however this change cannot only be made in the anodisation tank. The pre- and post- rinse tanks must also be compatible, as must any other tank stages that an operator runs.

Switching to 'greener' chemicals throughout the production line presents issues on two fronts - there are fewer suppliers and the up-front price of the chemicals is considerably higher (although the disposal costs are lower).

4.5: Alloy Selection

In theory, any anodisation process can be applied to any aluminium alloy. In practice this is very much not the case. The choice of alloy must take into account the role of the part being made as well as the anodisation process which will be applied to it.

The expertise of alloy selection for function, and the expertise of alloy selection for anodisation does not often overlap - which can present issues for both customer and anodisation operator.

Communication of specifications and requirements at an early stage of the design process is of benefit to all parties to avoid unnecessarily troublesome alloy/process combinations.

An anodiser may be expert at a certain process however they cannot directly apply that experience to a new alloy without changes to their process parameters. It may also be impossible to produce a high-quality result in dyeing and colourisation processes on certain incompatible alloys.

4.6: Geometrical Accuracy

Anodisation is usually the final stage of finishing for a component - it may already have features machined into it which must remain within tolerance after the anodic film has been formed. Anodisation is grown outwards from the surface of the metal and this must be taken into account when tight tolerances are required (eg. interference-fit parts on automotive engine components).

Allowing for the outward growth caused by the anodic film is feasible under the assumption of a perfectly uniform coating (although it may require special tooling eg. undersized dies and oversized taps). Unfortunately the growth of the film is not uniform for complex geometric shapes, due to issues with localised electrical field effects and electrolyte concentration changes. A specific example of problematic geometry is a narrow but deep bore hole - the anodic film will be thickest in the area close to the entry/exit surfaces and thinner in the middle of the bore.

4.7: Repeatability

Producing anodic films of consistent thickness across different runs of parts is essentially a manual process, requiring measurement and adjustment of total dwell time. The properties of the anodised finish are dependent upon all process parameters - adjusting to maintain one property may adversely impact another. Making adjustments run-to-run to ensure a particular property of the anodised finish is consistent does not guarantee that all aspects of the job are similar between batches.

Colour-matching is a challenge between batches (even of the same part and material). Dye baths in particular exhibit a dramatic change in the colour of parts within two weeks of a full chemical change, then stabilise to a slower decline in colourisation. The dye uptake properties of the anodic film also are unknown by the operator until the dye is applied which presents a further variable to compensate for.

In short, the repeatability of the process is dependent upon fixing all process parameters and raw material properties - any adjustments will trade one property for another (although this may not present an issue depending on the use case of the final product).

4.8: Uniformity

Anodisation is a surface coating however it does not change the surface texturing - and has been colloquially referred to as an 'error detector' for preceding processes because it very clearly shows any imperfections that were present. Therefore most of the efforts towards achieving a uniform finish do not lie in the anodisation process itself, but rather in the part preparation and handling. Mechanical marks, machining stresses and contaminants will all impact the uniformity of surface finish.

The orientation of parts in a dye bath can affect a uniform and perfectly anodised piece - long upright sections will tend to show a colour variation. Loading the pieces horizontally will produce a more consistent colour in each individual piece and the inherent variation will manifest as a subtle colour difference between the pieces. Dye uptake is primarily dependent on the porous structure of the anodic film and there is little that an operator can do to influence this.

4.9: Process Parameter Development

The major anodisation processes are described in Standards Documents and these are particularly detailed for Aerospace specifications. Despite the clear specifications these documents serve only as a starting point for anodisation operators.

In some respects the anodisation procedure can be considered like a recipe - and much like a chef will have a list of ingredients and cooking times, the actual making of the dish will involve skill and knowledge that is not included in the cookbook. Anodisation operators add value through their experience in developing exact procedures and parameter envelopes. They have the knowledge of which adjustments to make and when to make them in response to the trajectory of an anodisation job. For experts in a certain process, this is commercially sensitive information that can be on-par with a Trade Secret - the most established processes will incorporate decades of tribal knowledge and operational experience.

The process of developing the detailed procedure and defining the allowable envelopes of parameters requires deep knowledge and experimentation. Alloy type, electrolyte composition, chemical additives, tank parameters, part geometry, jig design and their relation to the anodic film properties must be understood and accounted for. The journey from new job specification to anodisation procedure takes weeks even for the most experienced operators. If a significant change is made (for instance, a new chemical process) then developing a new procedure can easily take months of effort and experimentation.

The implications of this difficulty are severe: anodisers will not want to change their process without a strong business justification, the significant amount of time spent in experimentation is time not spent in production (unless the company has a dedicated pilot line) and the up-front investment costs in new equipment or chemicals cannot be recouped until this process development work is completed.

4.10: Part Loading & Unloading

Parts to be anodised will be processed through several tanks - during these stages they will be lifted, transported dunked and agitated. The parts must remain securely attached to their jigs throughout this series of movements and this secure attachment must provide a clean electrical contact for the anodisation process. If air agitation is used in the anodisation tank then special care must be taken with regards to part orientation.

For large repeat runs, it may be possible to economically automate the loading and unloading of parts - however this is not the usual case for the majority of anodisers operating in Britain. Smaller batches of varying parts make up the majority of jobs for British anodisation firms and these must be manually loaded into custom jigs by skilled workers which is a labour intensive process.

The investment in jigs can be enormous, with titanium being a favoured material when the anodisation process allows for it. Some anodisation processes cannot be operated with a jig made from dissimilar metal to the parts, and in this case the aluminium jigs will be anodised during the process too. When an aluminium jig has been used it will need to be stripped back to bare metal before it can be re-used to process another batch.

Besides obvious loading failures like loose parts it is often unclear if the electrical contact between part and jig is sufficient until after anodisation has been completed - at which point visual inspection or other testing will detect failed pieces. Another point of failure can be the electrical contact between the jig and the power supply for the anodisation process - which can compromise an entire batch despite proper loading of individual parts.

For large runs of parts it may be more economical to load quickly and accept a higher failure rate than to spend an overly large amount of time ensuring that every single part is securely loaded. This trade-off depends upon a skilled operator that will generally load parts correctly and represents a directly human-driven factor in the performance of the process.

The manual loading of jigs also presents a vector for contamination because all parts will be individually handled by an operator. If procedures are not correctly followed (fresh gloves, clean working area etc.) then contaminants introduced by the operator may cause additional defects in the anodisation process. The loading/unloading process is generally resistant to automation due to the wide variety of jigs in use and the significant variations in geometry of the parts to be anodised.

4.11: Inspection & Testing

Anodisation is a chain of processes, each of which is reliant upon the previous link and largely unable to compensate for failures/defects in preceding operations (ie. issues accumulate and they cannot be undone after a part moves down the line). Ideally the success of each process would be verified before moving on to the next, however there are two issues with this approach: time and visibility.

The time that it would take to make a thorough manual inspection of every part as it passes from one tank to the next would reduce throughput of the line by an unacceptable degree and the automation of this task is not commercially feasible using conventional techniques.

The visibility of latent defects is also not guaranteed - there are issues that cannot be spotted even with a detailed visual inspection (eg. induced stresses in the micro-structure of the metal). These defects will only become apparent after the process that is sensitive to them has produced a compromised result.

Testing of parts is almost exclusively conducted in an off-line fashion, with the expectation that the output of the line will be correct if procedures have been followed consistently. If more advanced testing is conducted in a laboratory, the time lag between submission of test pieces and receipt of results can result in significant spoilage/rework for a high volume line.

4.12: Pre- & Post-Processing

The focus of this investigation is the anodisation process itself however it cannot be considered in isolation. The results of aluminium anodisation are heavily dependent upon the chain of events from part manufacture, preparation, sealing and transport to end-user.

Maintaining a clean working environment and proper storage, transport and handling procedures are the critical factors in ensuring a good result.

4.12.1 Part Manufacture

The choice of correct alloy for both application and anodisation process is essential to obtain a good result and long service life. The fabrication process of the part can also directly affect the quality of the anodisation (weld lines and metal stress will be clearly visible after anodisation and cannot be compensated for).

Parts with stringent geometric tolerances must take into account the thickness of the anodic film to be deposited. Multi-component parts must not have any other metals attached to them when being sent for anodisation. Any machining oils, polishing compounds or other substances left as deposits should be reported to the anodisation operator (so that they can be cleaned using the appropriate process) or the parts should be provided as thoroughly pre-cleaned.

4.12.2 Cleaning

Parts must be thoroughly degreased and decontaminated before entering the anodisation line and this level of cleaning is generally considered as a separate process from the anodisation itself.

If parts are not supplied by the customers as pre-cleaned then it is important that the anodiser knows which contaminants are present. Successful cleaning relies upon using the correct solvents that are able to remove the foreign substances from the parts and are chemically compatible with the anodisation line.

Remaining substances which are not cleaned from the parts may introduce chemical contamination to the anodisation tanks and compromise the expensive chemicals required at each stage - reducing their lifetime and impairing the performance for future batches.

4.12.3 Rinsing

Parts are usually rinsed in a succession of tanks, each time becoming 'cleaner' until they enter the working chemical tanks (etching, anodisation, dyeing). Deionised water is commonly used as the rinsing medium, however there are cases where specialist chemicals must be used for esoteric anodisation processes. If the local water supply is not sufficiently pure then the anodiser may operate a de-ionised water production plant to supply their rinse tanks.

Rinsing is performed between every stage of the process, and it is important to monitor the cleanliness of the rinsing medium to avoid introducing impurities to a batch.

4.12.4 Sealing / Dyeing

Immediately post-anodisation, the porous layer is described as 'open' and is vulnerable to uptake of foreign particles. In the case of a cosmetic coating this is desirable because it provides the mechanism for dyes to be impregnated into the anodic film.

Whether dyed or naturally finished the pores must be sealed before the part can be put into service. The sealing/dyeing tank must be maintained to a high standard of purity to avoid introducing contaminants into the final coating.

4.12.5 Transportation

Final finish parts should be packed in a manner that does not allow them to move against one another and cause surface abrasion. Any automated handling machinery should also be configured to avoid leaving handling marks on the components (this is especially relevant to extrusions and sheet material). These transportation recommendations apply before and after anodisation, especially in the case of parts supplied at final-finish by the customer.

4.13: Ductility vs. Corrosion Resistance vs. Adhesion

There is a tension between the film properties that requires a trade-off between fatigue resistance, corrosion resistance and adhesion strength. Large pores will increase adhesion but decrease corrosion resistance. Thick films are good for corrosion resistance but will be more prone to cracking under strain and flex. Consideration of these factors is particularly relevant for aerospace applications[2].

4.14: Profit Margins

Given that anodisation is akin to a recipe that could be perfected (assuming consistent raw materials), the least challenging form of production is large runs of identical parts. This large-scale consistent type of operation can be readily automated with robotic part loading/unloading, auto-dosing systems, machine-assisted part inspection and fixed working procedures.

The majority of large-run anodisation work is now carried out overseas and is priced at margins that British companies cannot compete with. The lower costs of overseas manufacturers are generally due to lower labour costs and, in some cases, lesser environmental regulation leading to lower operational overheads.

British anodisation now competes on high-quality, short-turnaround and small-run difficult jobs.

There are several cases of local synergies that render larger-scale aluminium anodisation services price competitive (eg. localised clusters of manufacturers that require anodisation services but do not wish to install their own lines) however this scenario is the exception rather than the rule.

Aluminium Anodisation companies may also offer additional consultancy services (design support) and processing services (polishing, chemical brightening) to increase the value of their offering. It is a common case that anodisers will provide additional coating services (eg. electrochroming, painting) because they already have the logistical infrastructure and business processes to handle finishing work. This can be beneficial to increase to increase the scope of their customer base. The installation of a process which demands higher cleanliness standards than anodisation will likely improve their anodisation performance. The downside of expanded services offerings is that additional environmental contamination may be introduced to the site.

5 Aluminium Anodisation Research

There were two major peaks in scientific interest regarding aluminium anodisation - its discovery in the mid 1800's, followed by a resurgence during the 1950's-1970's which was fuelled by the availability of improved instruments to inspect the morphology of the porous layer. This has resulted in a wealth of academic and non-academic literature which characterises the process in great detail.

Analysis of book publications (via Google Ngram viewer) shows that the mid 1990's saw a spike of interest around nano-material properties followed by another short revival in the mid 2010's investigating the reliable production of nano-materials and their possible applications.

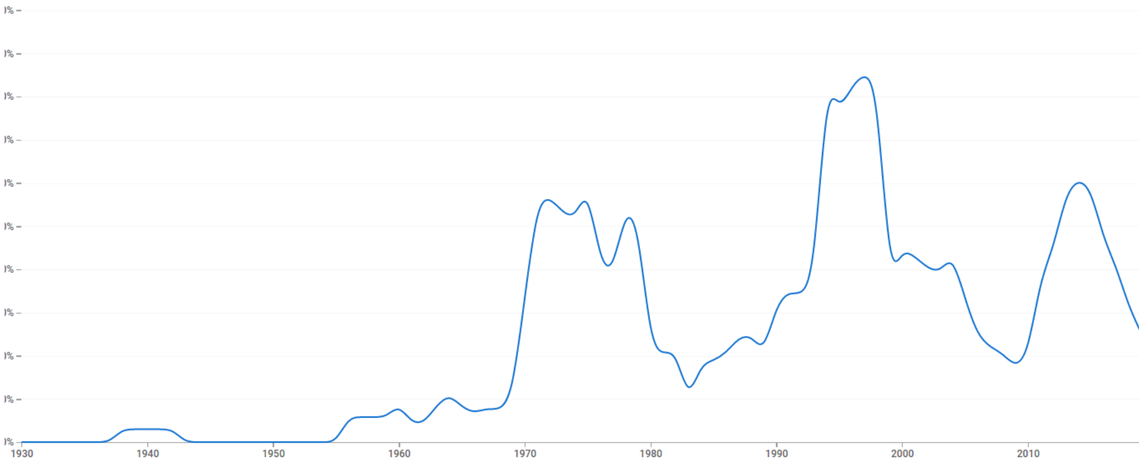


Figure 13: Google NGram of Aluminium Anodisation Book Publications

The practical industrial value of research work has concentrated much of the activity towards commercial R&D (with a concomitant reduction in publicly available literature). The Aluminum Anodizers Council[3] is a noteworthy repository of industrially focused research that can be accessed by paying members.

There is still ongoing research activity in the field, however aluminium anodisation is a well-established process that no longer presents a pressing demand for fundamental questions to be answered - with the exception of investigating the nano-material properties that can be exhibited by porous layer structures.. The remaining areas that are not completely understood do not present problems for the practical operation of the anodisation process.

The contemporary drive towards more environmentally sustainable processes may once again stimulate general research in aluminium anodisation. Many of the legacy processes that use harmful chemicals require outputs of a tight tolerance and high specification - transitioning these critical operations to environmentally friendly electrolytes and additives presents a significant challenge for the industry.

Following a brief overview and history of research into anodisation, two research areas that are relevant to the proposed digitalisation pathway will be discussed.

5.1: Overview & History

Some of the early work of scientists in the 1800's and early 1900's investigating anodisation remains relevant today - particularly the characterisation and description of the electrochemical reaction that underpins the process, especially the Tafel equation which describes the total polarisation of the electrochemical cell[4]. Work was also undertaken to investigate different electrolytes, to characterise the properties of the anodic film and to develop a variety of treatments and applications[5].

In the second half of the 20th century, new tools and methods allowed direct observation of the structure of the anodic film. Improved knowledge of metallurgy and the ability to accurately measure the properties of the anodic film led to the characterisation of the relationship between layer thickness and formation voltage[6] and improved the understanding of the structural effects of additives[7]. Theories of the mechanism of pore formation were refined and debated[8] [9] [10] - and indeed are not completed settled to this day. Lively research continues into the nano-properties of aluminium anodic oxide which can be observed when anodising highly pure aluminium under tightly controlled conditions[11].

The publications of Dr. Jude Mary Runge span academic and industry journals, and her book *"The Metallurgy of Anodizing Aluminum"*[12] is a comprehensive treatment of the science of aluminium anodisation. Any review of anodisation literature must also make mention of Dr. Arthur William Brace, who is regarded as the "Father of Anodising" in industry and academic circles.

The review produced by Runge[13] and the reference book authored by Brace[14] together provide a comprehensive accounting of anodisation theory and fundamental practice.

5.2: Estimation of Anodic Film Thickness & Pore Morphology

The aluminium anodic oxide (AAO) film thickness is a critical specification of anodised parts which leads to an interest in being able to predict or estimate this property. There are many techniques to measure the final thickness of the deposited coating, however determination of the thickness in real-time from process parameters or indirect information remains a challenge. The pore structure is not normally specified in the standards for conventional anodisation work, however this structure is directly related to the final properties of the AAO film and therefore can be considered as an implicit specification.

5.2.1 Data Driven Estimation

Data driven techniques to estimate film thickness rely upon accurate measurement (and identification) of important process variables and the derivation of their relationship to a set of ground truth film thickness measurements. This approach is labour intensive, requires extensive experimentation and there is a question over how generalisable results will be across processes, alloys and additives.

Rashid et. al[15] conducted an investigation into chromic acid anodisation using Box-Wilson experimental design to optimise a polynomial model incorporating temperature, voltage, time and electrolyte concentration. They concluded that the interaction of variables does not constitute an important dynamic in the prediction of anodic film thickness, and that temperature and time are the dominant factors. Mubarok et. al[16] performed a short series of experiments investigating polynomial models to characterise the thickness and weight of AAO film and their results also show that interaction of variables do not contribute significantly to the results.

Akolkar et al.[17] used the numerical modelling "CELL DESIGN" CAD software (no longer available) to investigate the effect of AAO film growth in a controlled laboratory setting. They achieved accurate predictions of non-uniform thickness across a variety of anodisation voltages, bath temperatures and anodisation times. Critical model parameters were measured experimentally and input into the CAD software.

The literature on data driven models shows that low order variable interaction does not appear to be a significant factor in modelling AAO growth and that useful predictions can be made of the characteristics of the AAO film under known and controlled conditions. It remains to be seen if this can be translated to industrial applications and there is an expectation that a significant amount of data would be required to create usable commercial models.

5.2.2 First Principles Modelling

The exact mechanics of anodic film formation (specifically the porous layer) have not yet been completely settled, however a considerable body of knowledge exists regarding the characteristics of its structure and the relations of this process to different additives and alloys. Modelling anodic film formation using detailed information of the materials and process parameters may be feasible in controlled and consistent circumstances.

There are a number of competing models of AAO pore formation which include: a combination of mechanical stress and electrical field effects[8], convective flow of material initiated by growth stresses[18] and, ionic migration driven by the stress of metal atom diffusion at the interface[19]. These models all agree that stresses in the material are a key aspect of the formation of porous AAO.

Runge[20] outlines the important factors in creating a model of anodisation at the electrochemical level, including consideration of the substrate characteristics and the manipulation of pore morphology manipulation through current density. Runge reiterates that the Tafel equation forms the foundation for modelling the process - however it must be extended to include interfacial phenomena (surface polarisation effects, texture and contamination) and concentration polarisation effects due to intermetallic impurities or contaminants that remain after cleaning. Other variables that affect growth include suspended particles in the electrolyte, surface asperities in the anode and microstructural properties of the aluminium.

Garcia-Vergara et al.[18] show that pore growth arises from flow of material underneath the cell walls by means of an embedded tungsten tracer. Their work studies in detail the growth rate and morphology of the AAO produced with a phosphoric acid electrolyte. They observe that pore diameter correlates with anodising voltage at an approximate ratio $1nmV^{-1}$ however they note that the precise values depend upon current density and the exact composition of the electrolyte, and do not elucidate this relationship further.

Despite a lack of consensus, the models available appear to be sufficient to relate film thickness and pore morphology to process and material parameters. No evidence of using these models to formulate industrial process parameters (with the exception of research into nano-material production) was found.

5.2.3 Real-time Measurement of Film Thickness

Monitoring the growth of AAO in real-time requires equipment that is able to take measurements in an aqueous environment (ie. operate in the anodisation tank). In 1989, Deakin et al.[21] successfully made in-situ measurements of AAO thickness using a Quartz Crystal Microbalance - however this method requires direct contact with the substrate and is undesirable for practical processes.

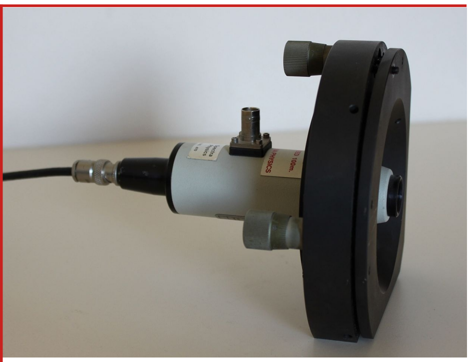


Figure 14: Fabry-Pérot Inferometer

Non-contact techniques that have been demonstrated in a laboratory setting to measure AAO thickness in-situ include: spectroscopic ellipsometry[22], electrochemical impedance spectroscopy[23][24], laser-reflection interferometry[25] and Fabry–Pérot interferometry (which can be achieved with non-coherent light sources)[26].

Of particular interest is electrochemical impedance analysis because it returns several pieces of information via capacitive and inductive loops being observed at varying frequencies. The observed quantities relate not just to AAO thickness but also to its microstructure which may enable in-situ real-time sensing of additional AAO film properties. It may also be a feasible technology to retrofit to existing equipment.

5.3: Process Development

Critical processes have been developed at considerable expense over the course of decades, leaving industry relatively resistant to disrupting these practices. Researchers who are not constrained by the requirements of a commercial operation are well placed to contribute to development and testing of replacement processes which substitute harmful materials for more environmentally friendly alternatives.

Anne Deacon Juhl is a well-known researcher/consultant in the industry has published on the subject of implementing more energy efficient pulsed mode anodisation[27] [28] [29].

The general paucity of publications regarding anodisation process development is most likely explained by the fact that those with the expertise to speak upon the matter are operating as consultants, not academics. This research landscape also underscores the maturity of the aluminium anodisation process.

6 Digitalisation of Aluminium Anodisation

Aluminium Anodisation is a process that relies upon strict working procedures developed over time, the skill and experience of operators and, a significant amount of human intensive oversight and monitoring. Defects are often discovered after the process which is sensitive to the underlying cause has already been completed, resulting in rework or spoilage. To borrow a piece of control terminology - aluminium anodisation is an open-loop process: pre-defined steps are followed and the output is assumed to be good (until it's not).

The journey of manufacturing digitalisation takes a company through networking of processes, embedding sensors, creating real-time operational visibility, building a knowledge base and integrating artificial intelligence into operations. For aluminium anodisation this could take the form of parts traceability as they move through the different processes, decision making support for operators and, enhanced real-time monitoring of plant, job and process.

6.1: Architecture

6.1.1 Template for Digitalised Aluminium Anodisation

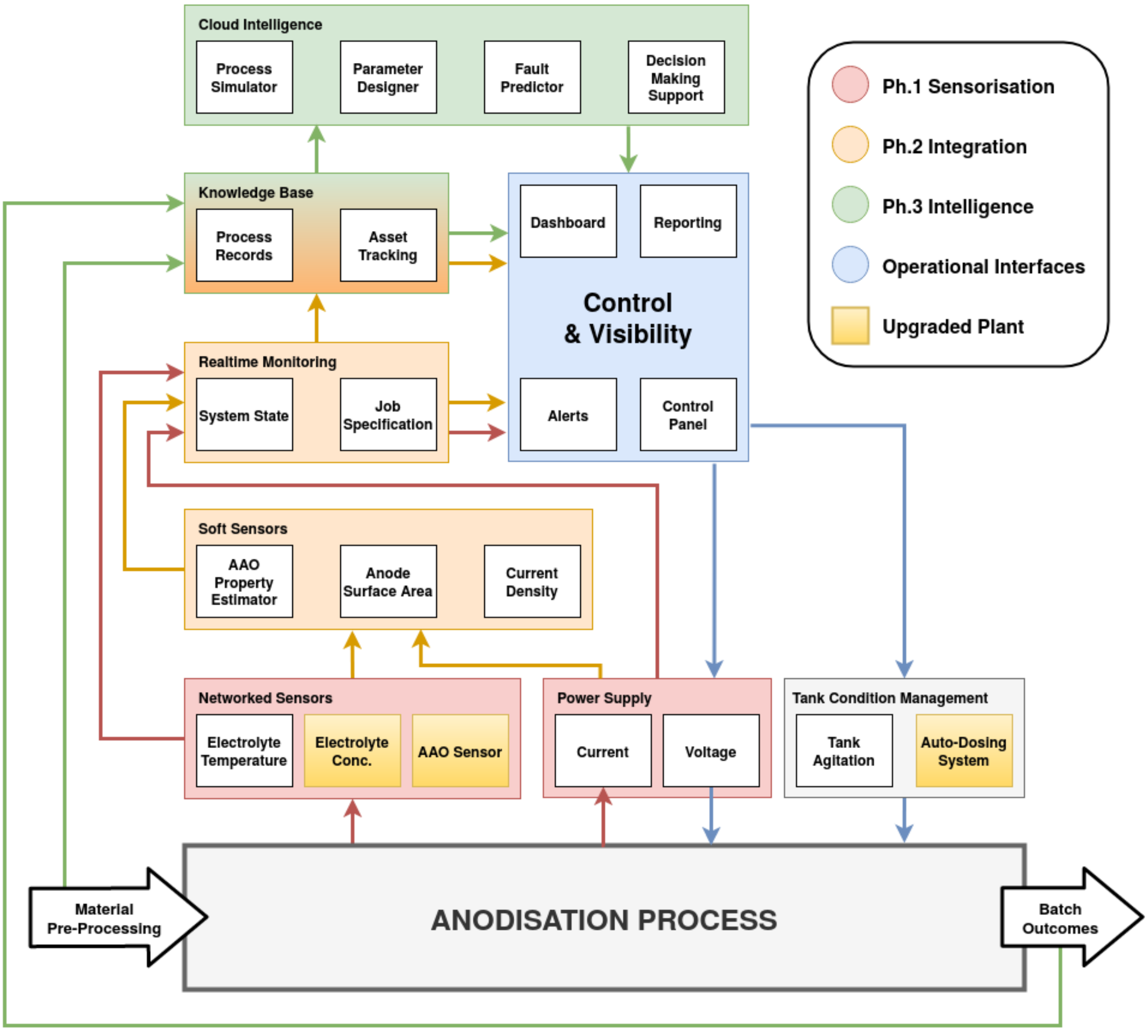


Figure 15: Aluminium Anodisation Digitalisation Architecture Overview

A general architecture for a digitalised anodisation process is split into three phases: Sensorisation, Integration and Intelligence. Three pieces of equipment not commonly found in anodisation lines are also specified: an in-situ electrolyte concentration sensor, an in-situ anodic film sensor and an Auto-Dosing system. These optional upgrades are not required to realise the benefits of digitalisation however these technologies will magnify the value and are expected to become more widely deployed as innovation work drives down prices and increases availability.

Each anodisation operator will have specific requirements based upon their existing plant and software infrastructure. Interoperability between different vendors' products is a common issue in the implementation of digitalised manufacturing systems. The provided example implementation will present an approach to accomplish each phase of the digitalisation process based on a notional site with existing IT infrastructure and a partial process monitoring network available.

The phased approach presented is intended to be compatible with existing systems (where present) and the recommendation is made that duplication/replacement of infrastructure should be avoided during a system integration (ie. use what is already available and add only that which is missing). Note that the choice of sensors, systems and software stack in a practical system integration should be reviewed with respect to the particular requirements of a given site.

6.1.2 Phase 1: Sensorisation

The first phase of digitalisation involves connecting plant infrastructure to a common system so that an overall view of the process can be established in real-time. This may be accomplished through retrofit connection to existing plant and controllers or through installation/upgrade of systems.

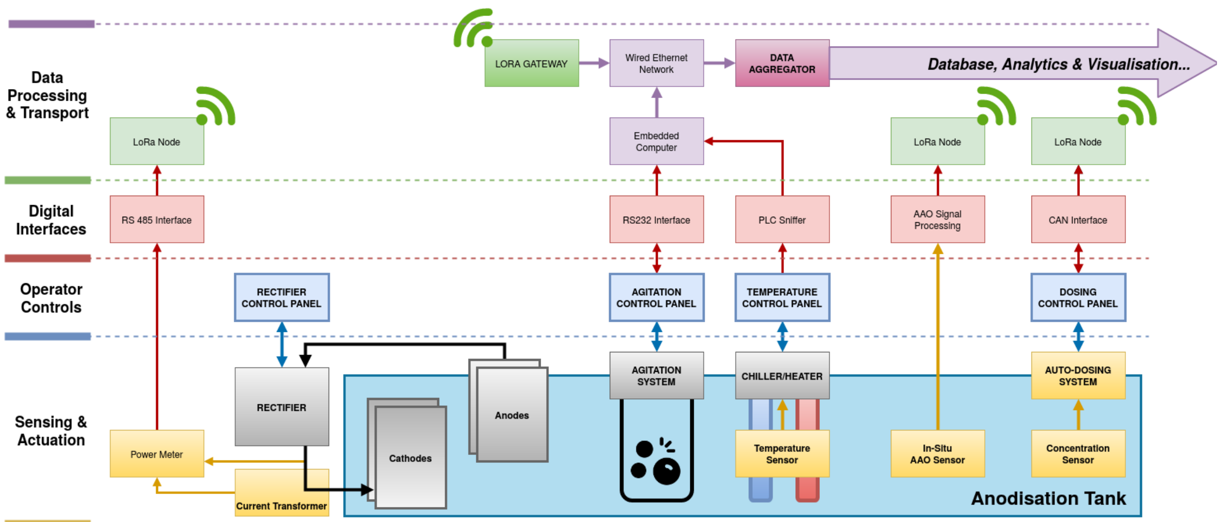


Figure 16: Phase 1 - Sensorisation

Wireless sensor technology (eg. LoRaWAN) enables low-disruption installation of data acquisition systems and can be integrated with existing plant through the use of protocol adapters (eg. RS485 Modbus) or direct sensing (eg. PLC sniffing / programming) of analogue/digital signals. If SCADA infrastructure is available it is possible to connect embedded computers to acquire data without requiring explicit integration into the existing information management system.

It should be noted that data acquisition can be relatively easily accomplished - however the integration of control and actuation requires robust interfacing. If the intention is to automate or centralise line control, functional bidirectional interfaces should be installed during the sensorisation process rather than passive signal capture technologies. The latency of wireless networks should also be considered (10's to 100's ms) - it can be helpful to apply the rule-of-thumb that they are suitable for set-point manipulation but not process control signals.

Figure 16 demonstrates an anodisation tank that has been sensorised using a combination of existing sensors (temperature), retrofit sensors (rectifier power measurement) and novel sensors (AAO and Electrolyte Concentration). Wired and wireless networks are connected to a data aggregator (which is typically a small on-site server) that serves as a nexus for all sensor and process information that is being acquired. At this stage of digitalisation, real-time readings of all networked equipment will be available at a single point. It would be possible to install a terminal or display that shows the status of the entire line if so desired - representing modest but immediate added value.

6.1.3 Phase 2: Integration

Once real-time process information is available, the next step is to connect important knowledge and records from other sources, often contained within the Enterprise Resource Planning / Material Requirements Planning system. Digitisation of resources may by required if record keeping is pen-and-paper based, however in some cases it is possible to use pattern/template recognition to reduce this burden (eg. identifying that certain combinations of process parameters correspond to specific jobs). Due to the dependence of the anodisation process upon prior operations, the history of the batch to be anodised (material spec., cleaning processes, rinsing processes) is of critical importance to predict and measure performance. Recording the outcomes of finished batches (tests results and failure notes) will be equally important in building predictive performance models.

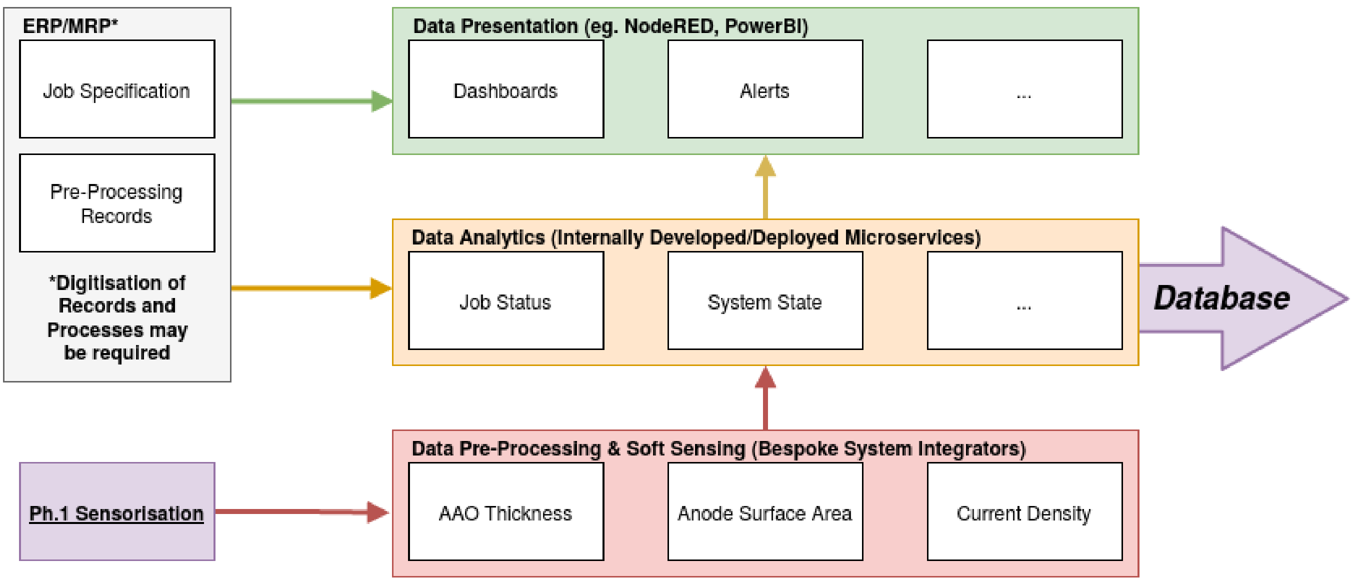


Figure 17: Phase 2 - Integration

With the information sources in place (raw data and job information) the three layers shown in Figure 17 are required to build a useful integrated platform: Data Pre-Processing, Data Analytics and Data Presentation.

- **Data Pre-Processing (and Soft Sensing)**: This involves interpreting the raw sensor readings and process parameters as semantically meaningful process states (eg. voltage ramping, steady state film growth) and deriving additional attributes (eg. performing calculation of current density via estimation of the anode surface area). These pre-processing steps should be 'set-and-forget' operations powered by stable and consistent algorithms that produce high quality data.
- **Data Analytics**: The combination of job information with process state and batch attributes enables useful measurements, insights and predictions to be made. This could take the form of batch end-time prediction (and the verification that this is in-line with the production

schedule), anodisation tank condition monitoring and system efficiency metrics. These production critical, customised applications would be expected to be locally hosted (not dependent upon an internet connection) and tailored to the operations of a specific company (with the assistance of a third party where appropriate).

- **Data Presentation:** The data presentation layer is an essential component of the overall system because it acts as the human interface to the digitalisation system. The choice and style of presentation is highly dependent on working practices and existing infrastructure - it may take the form of dashboards, spreadsheets, push-notifications, shop-floor alarms etc. Tools like NodeRED and PowerBI empower companies to build and customise their own visualisations.

The topic of databases and historical record keeping has not been considered thus far in this phase - this deliberate choice is to demonstrate that there is benefit at each stage of digitalisation without the requirement to complete the whole journey immediately. In practice, the indicated database connection would usually be built at this stage to support data analytics applications - however it is not absolutely necessary.

At this stage of the digitalisation journey several valuable benefits will emerge - visibility of process and performance (including a shared reality from shop-floor to management through evidence based metrics), customised alerting and error detection (resulting in reduced fail rate and decreased operator cognitive burden) and real-time process insight (some enhancements will be dependent upon installing additional sensors).

6.1.4 Phase 3: Intelligence

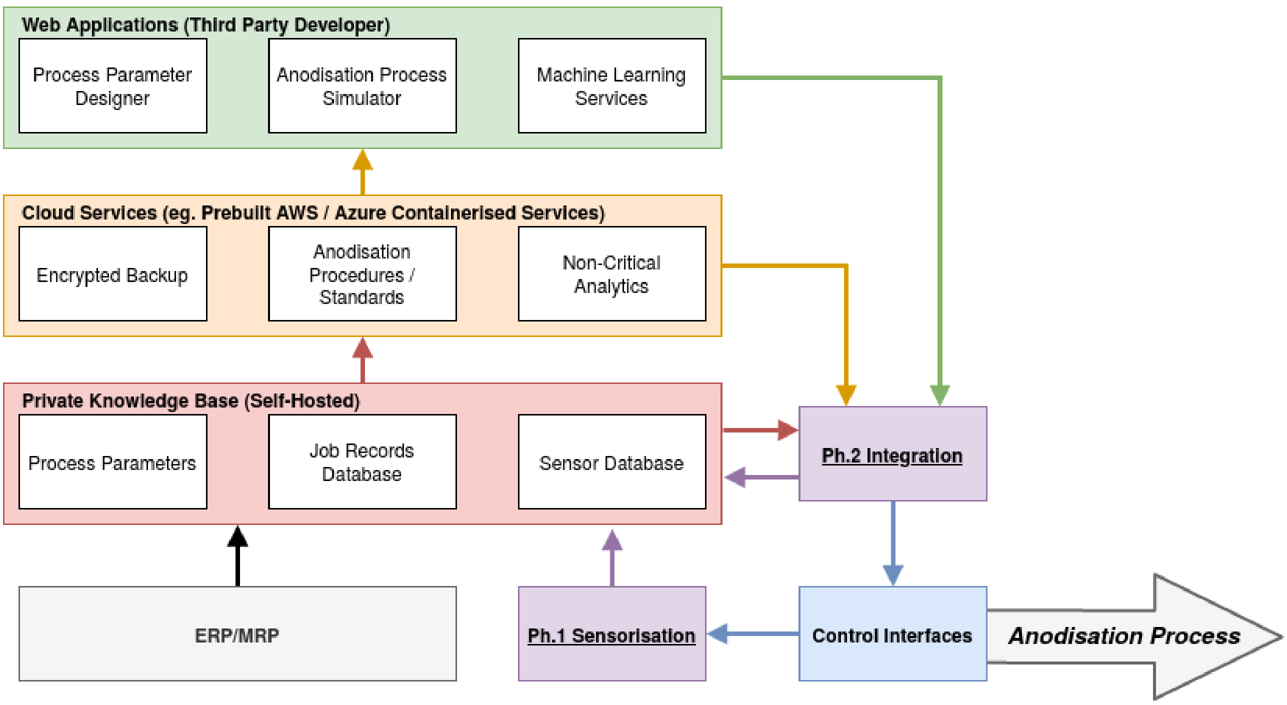


Figure 18: Phase 3 - Intelligence

Having built infrastructure in Phase 1 and Phase 2, the system can now be enhanced with the intelligence that powers the evolution of the workflow. Good quality streaming data is available from the production floor and the important job specifications are available from the ERP/MRP system. To move beyond monitoring and towards intelligence requires building a knowledge base and connecting additional data sources.

A three layer model is proposed for a flexible and powerful digitalisation system: Private

Knowledge Base, Cloud Services and Web Applications.

- **Private Knowledge Base:** Process records will naturally be built up over time as the system runs however there will be additional value in historical records (eg. notes on process development and the results of those experiments) and other knowledge (eg. empirically discovered process constraints) which should be digitised and made centrally accessible. This information tends to be commercially sensitive and should be securely hosted (either on private IT infrastructure or a trusted cloud provider).
- **Cloud Services:** A proportion of the required infrastructure and services are generic and can readily be hosted in cloud infrastructure which reduces the setup and maintenance burden on internal IT services. This approach creates flexibility and scalability as a company's IT services evolve and can play an important part in building a resilient system.
- **Web Applications:** There are difficult challenges to digitalisation that are common across the anodisation industry - some of which can be solved with generalised approaches. These solutions could be developed by third party organisations, sold as products and delivered as web applications - allowing a company to make use of advanced statistics, modelling and machine learning tools without needing to operate the required infrastructure or invest significant resources in research and development. A route for generalised industry tools to be easily integrated into production will encourage researchers and innovators to solve the challenges of anodisation and create impact.

Each of these three layers is connected back into the system from Data Presentation down to production line actuators, embedding intelligence from the cloud to the shop-floor.

This is one possible vision for the intelligence layer of a digitalised anodisation production system. Each company will have their own operating procedures, their own approach to IT infrastructure, and their own specific challenges to address and goals to achieve. This phased approach aims to provide value at all stages and the layered structure is designed to be tailored for each manufacturer's digitalisation journey.

6.2: Barriers to Digitalisation

6.2.1 System Interoperability

Integration of existing systems is notoriously hard and most readers will be familiar with the problem of data silos and proprietary interfaces being glued together through human labour rather than digital protocols. In undertaking a digitalisation program, a company has the opportunity to embrace this reality rather than try to eradicate it.

Standards are created every 5-15 years whilst mechanical hardware can have an operational lifetime of up to 100 years. Automation and IT hardware tends to last for around 10 years and the software and semantics it uses for interfacing are shifting sands that have a contemporary longevity measured in months[30]. Significant effort is being expended upon creating universal standards and promoting interoperability but the incentives of vendor lock-in and the piecemeal nature of operational plant upgrades make a standardised landscape unlikely in the medium term future.

The proposed approach to digitalisation maintains focus on the matters of importance, and makes no assumptions of the underlying technologies. In essence the procedure is to interface with what is already present and add only the elements which are missing. This technologically agnostic attitude may smooth the road on the digitalisation journey, but once deployed, how can it be ensured that the digitalisation system itself does not present the same issues to future upgrade efforts?

If standards are constantly changing and IT practices are always evolving, then choosing the latest and greatest standards will still put a lifetime on the accessibility of the system to future integrators. A powerful mitigation to this is the choice of open-source software, self-hosted solutions and the maintenance of detailed documentation.

With open-source software the risk of technology sun-setting is greatly reduced, and vendor lock-in is practically eliminated. Quality documentation enables replication across sites, improves consistency and guarantees that future maintainers will be able to fix, augment and extend the system. Whilst building the expertise to self-host services and maintain a digitalisation system is a considerable resource expenditure, perhaps it should be considered in the same light as hosting an on-site workshop for production line repairs and maintenance.

6.2.2 Security of Trade Knowledge

Recording the tacit knowledge within an organisation comes with risks attached - the wisdom and experience represents a significant proportion of the value that a company brings to their customers. Operators may also be uncomfortable digitising their expertise, with the fear of being automated into redundancy.

The integration of cloud services and third party applications that require access to company records and operating procedures can pose a security risk even when good security practices are followed (for instance, from social engineering to compromise access systems).

Companies that benefit from artificial intelligence applications are likely to use third-party expertise to develop these tools - will the lessons learned from their data be used to improve a tool which is then sold on to their competitors?

6.2.3 Sensor Cost and Availability

Novel sensor technology has been included in the proposed digitalisation framework which is not currently readily available to industry. In-situ aluminium anodic oxide sensing has been successfully demonstrated in lab conditions using a variety of techniques but despite the commercial viability and desirability of the technology, it is not widely deployed. The development of the hardware and the signal processing algorithms of these sensors is not a viable undertaking for most firms that specialise in aluminium anodisation.

Monitoring of electrolyte concentration and pH is an offline process, samples are taken and analysed, then adjustments are made to maintain nominal conditions in the anodisation tank. In-situ online sensing of these tank parameters is a key system requirement for the benefits of digitalisation to be fully realised. This form of monitoring is included in costly auto-dosing systems however it is not often installed outside of that context.

6.2.4 Difficulty of Automation

Aluminium Anodisation is a labour intensive process, particularly part loading/unloading and inspection. These activities are resistant to automation due to the variability in part geometries and jig design. The phrase "digitalisation is not automation" must be emphasised when considering the value that can be added, with a focus of reducing the burden upon operators.

Assistance could come in the form of flagging job types with a particularly high fail rate, computer-vision enhanced inspection tools and better process visibility for operators which may be supervising several anodisation tanks simultaneously.

6.2.5 Established Working Practices

The formula for a successful anodisation process is exactly that - a formula. Efficient and consistent anodisation providers have developed their working practices and process parameters over the course of decades and are capable of reliably producing excellent quality work. In the case of defects, experienced operators have established mitigation strategies and troubleshooting procedures.

Digitalisation systems must be able to demonstrate their value in the face of proven-effective working practices. To undertake the digitalisation journey there must be willingness at all levels to engage with the new technology and build trust in the data, metrics and recommendations that are produced.

6.3: Costs, Risks and Benefits

Several risks and costs of digitalisation are common across industries: the capital expenditure on new/upgraded equipment and sensors, the time cost in systems integration/setup and, the risk of disrupted production (due to changes in working practice and plant interfaces).

Aluminium Anodisation is a thoroughly established process - its characteristics are well understood by operators who have developed procedures and methods to address both the major and the subtle challenges. It can be difficult to justify a business case for the investment and potential disruption involved in embarking upon the digitalisation journey when operations are running well. This leap of faith involves costs (capital expenditure and time resources), risks (will the new system disrupt production?) and benefits (operational insight and reduced workload).

The degree of human input to the process must be reduced to realise the benefits of digitalisation, but this implies the need to loosen the reins on a process which is traditionally very tightly controlled. The risk of potentially discarding hard-learned lessons that have been wrung from years of experience is not trivial, and thankfully that risk does not need to be borne as a single sweeping change.

Most anodisation companies will make use of a significant amount of human labour to accomplish each step of the process. It has been earlier stated that a large proportion of anodisation work is resistant to automation and digitalisation does not change this fact. The approach to digitalisation should focus on making difficult work easier and removing the simple manual interventions through intelligent technology - evolution, not revolution.

Two major potential applications are real-time oxide thickness monitoring and intelligent anodisation process parameter development. Real-time oxide thickness sensors eliminate the need for test pieces within a batch and can easily be programmed to halt anodisation when the correct thickness has been achieved. An intelligent program which supports the development of new anodisation parameters could enable operators to quickly define optimal process settings (and their envelopes) through a series of rapid experiments to characterise the job requirements.

Implementing these technologies would not force a change in working practices - but they would enable it. The cost can be clearly defined by system integrators at the outset, the risk can be almost completely mitigated (engage with the system as much or as little as desired) and, the change in working practices can be as gradual or as rapid as the user wants. Trust can be built in the system before it is relied upon and the framework will be in place for the future evolution of working practices.

6.3.1 Gap Analysis

Current State	Goal State	Gap	Action
Oxide Thickness is manually verified to define stop time of anodisation process	Automatic and Real-time Knowledge of Oxide Thickness	In-Situ Sensors not widely available	Reduce cost of lab-proven in-situ oxide sensors
Process Parameters are developed based on experience	Intelligent process development supported by private records	Process models and software not accessible	Develop software platform and undertake experiments to characterise process
Defects caused by issues only apparent after processing	Detect issues and fix before they become problems Flag difficult jobs for extra care	Manual processes and time constraints make it unfeasible to find all issues	Apply computer vision and novel imaging technologies to support inspection Analyse failure records and job specs to identify problematic scenarios
Oxide Properties are manually tested	Oxide properties derived from sensors, process records and job specification	Advanced Sensors and models not available	Develop and test AAO sensor and signal processing technology
Strict working procedures to maintain quality	Adaptive processes that compensate for conditions	Insufficient sensorisation Lack of opportunity for testing new approaches	Embark upon digitalisation journey and build confidence in technology

6.4: Suggested Applications

6.4.1 Film Thickness Monitoring

Controlling the thickness of the aluminium oxide is critically important and this is normally achieved via manual means - removing a test piece early, measuring its film thickness and calculating the remaining runtime of the batch.

Embedded non-contact sensors could measure film thickness as it forms, alerting the operators to remaining runtime and enabling tighter tolerances with lower labour intensity. Well-established processes with consistent material input may be able to use soft-sensing via tank conditions and process parameters to provide estimates of film thickness without requiring additional sensors.

The consistency and quality of anodic films are increased with the added benefit of unusually fast or slow film formation flagging the possibility of issues to be investigated.

6.4.2 Process Development Support

The move towards greener operations and the rising costs of using environmentally harmful substances will stimulate movement away from the traditional electrolytes and additives. British anodisation is also under pressure to be flexible with job and alloy specification. These factors necessitate the development of new anodising procedures, along with the time-consuming refinement of the process parameter envelopes.

A sensorised tank paired with artificial intelligence could quickly define voltage profiles, run-times and tank conditions for any combination of alloy and electrolyte. These initial envelopes could be refined based upon the results of a small number of experiments and combined with a company's private anodisation records to learn the characteristics of their own particular systems and working practices.

Time, mental effort and material wastage are all reduced in the paradigm of intelligent process mapping, whilst flexibility, adaptability and responsiveness are all improved.

6.4.3 Parts Traceability

Defects are usually caused by latent issues within a part before it has been anodised. The anodisation itself cannot normally compensate for these problems (eg. an insufficiently cleaned part with contaminants remaining on it). The history of previous processes is important information when assessing the quality of final parts and tracing faults/defects in the anodisation output.

A full history of each individual process in the anodisation line (tracking time, plant parameters, test results, parts and their neighbours within a batch) could be combined with information about the customer/supplier and historical performance of the same. This data combination would be able to produce knowledge about the expected performance and consistency of a given job.

Difficult jobs could be flagged to operators to alert them that the work may require additional attention (or indeed, a modified procedure). Tracing of defects to their cause would be supported by the ability to cross-reference all parts with their path through the factory.

6.4.4 Process Parameter Auto-Adjustment

Anodisation makes stringent demands on process parameters and tank conditions - deviation outside of the tightly defined envelope will result in poor quality output. Automatic adjustment of parameters could be made possible if tank conditions are measured and modelled.

Self-tuning parameters could enable operation within a wider envelope through automatic compensation for deviations in conditions, potentially extending the lifetime of chemicals, improving the quality of ambient temperature processes and improving resilience to production disruptions.

6.4.5 Parts Inspection

Errors accumulate during the chain of processes that make up anodisation and tend to become apparent when the damage cannot be easily undone. Checking parts for cleanliness and defects is a labour intensive manual operation that is generally accomplished by visual inspection.

Modern computer vision systems can be integrated into hand-held devices which could highlight problematic areas for closer inspection or potentially make a pass-fail judgement independently. Integration of additional vision technologies like hyper-spectral imaging could further assist operators in spotting latent issues before they become defects.

Integration with a parts tracing system would assist with fault analysis and empower a company to optimise their processes using evidence based actions.

6.4.6 Electrical Fault Detection

Improperly jigged parts and poorly connected jig-to-rectifier connections cause poor quality results, spoilage and rework. A private database of historical voltage-current profiles could be automatically generated by networked power supply systems to create an expectation of performance tailored to specific plant.

Repeat jobs that are known to be out-of-spec could be detected and flagged automatically - before an improperly jigged job is anodised. The electrical connections of high value work could be automatically verified to avoid spoilage and increase operator confidence. These benefits could be realised without needing to discard the large investment in existing jigs.

7 Summary & Recommendations

The process of aluminium anodisation is a mature and well-established activity, powered by a wealth of experience and knowledge within the sector. Working practices have been refined along the history of the industry, however the off-shoring of manufacturing to reduce costs has decreased the volume of work undertaken in Britain - despite the competence and performance of the sector.

The ability to offer multiple finishing services, produce consistently high quality work, innovate on processes and offer consultancy/advice to customers are the primary competitive qualities of British anodisation. Successful companies have refined their procedures and process parameters to produce excellent work - however this remains a relatively inflexible and labour intensive process.

The anodisation of aluminium is not a stand-alone process - it is dependent upon supporting activities (polishing, cleaning, rinsing, etc.). These surrounding processes strongly affect the quality of the anodisation and issues caused by a preceding process cannot be corrected by the following process which results in the accumulation of defects.

The common defects in anodisation are well documented in technical and academic literature which assists in the troubleshooting of the process. There are many combinations of alloys, finish and additives possible - knowledge of these interactions and the ability to make good choices when specifying a job remain subject to expert knowledge rather than look-up tables.

Research into industrial aluminium anodisation is no longer widespread; most of the contemporary work is focused upon the nano-material properties. The scientific and technical aspects of the aluminium anodisation process are comprehensively covered by the collected work of Jude Mary Runge and Arthur Brace. The dynamics of anodic aluminium oxide formation are well understood and characterised despite the exact details of anodic film formation remaining the subject of some debate.

There is useful research into data driven estimation of anodic film properties that has not found wide use within industry. In-situ anodic film measurement has been demonstrated repeatedly in lab environments with technology that is commercially feasible but has not been developed into a widely available commercial product.

Further automation is rarely a suitable choice for anodisation work in Britain with the cost and disruption outweighing the benefit in most cases. Digitalisation should therefore focus upon operator support - reducing the need to make estimations and assisting in the tuning of the process procedures.

Moving towards a digitalised process in Aluminium Anodisation could be structured in 3 phases: Sensorisation (real-time measurement of tank conditions and film properties), Integration (asset tracking and linking to ERP/MRP details) and Intelligence (AI applications to support process parameter design and predict issues with jobs/plant).

Any framework must be able to securely store company process information because this often represents a significant degree of the value-add that a given anodisation operator offers. As a counterpoint to private company knowledge, a good digitalisation implementation should also allow scope for third-parties to solve the difficult modelling/sensing problems and offer these solutions across the industry (with minimal additional set-up on the part of the anodiser).

The main barriers to digitalisation are legacy equipment (lacking networked communication), cost and availability of sensors and, the risk of disrupting established work practices. A flexible approach to digitalisation should be undertaken to mitigate these issues - integrating/retrofitting with existing equipment (only requiring that which is missing to be installed) and supporting operators (offering insight to issues and process, instead of re-writing working practices).

A successful digitalisation strategy would result in reduced operator workload (cognitive and physical), increased responsiveness and flexibility (ability to quickly develop and verify processes) and a rich record of job specifications and outcomes to power future development.

7.1: Research & Development Recommendations

This investigation of the aluminium anodisation sector in Britain has identified several challenges which are suitable for follow-on work in the Research and Innovation spheres.

Whilst the fundamental research remains largely focused upon the nano-material properties of aluminium oxide, there is work to be done in translating models of anodic growth from the lab to an industrial environment. The in-situ measurement of anodic film thickness is not readily available to industry despite several commercially viable technological approaches being demonstrated in the lab environment.

7.1.1 Research

Film Thickness / Property Models for Practical Environments

A variety of aluminium oxide growth models have been proposed and tested in the literature. It is clear that contaminants/additives strongly affect the growth behaviour however the specific reactions are not well defined. There is a need to investigate the prediction accuracy and sensitivity of anodic film growth models across a selection of alloys in the presence of a range of commonly observed additives and contaminants with the goal of producing a generalised model.

Anodisation Process Simulator

Simulation of the anodisation process has been accomplished using a variety of numerical and first-principles models which have shown that it is feasible to make accurate predictions when parameters are known and tightly controlled. Techniques to quickly determine and verify model parameters from a limited number of readings/experiments with regards to a variety of tank geometries and process values have not yet been developed.

Design of Experiments for Parameter Envelope Development

Nominal anodisation process parameters are arrived at through practical experimentation and the edges of the parameter envelopes established through failed pieces. The scientific experiments conducted to characterise the results of anodisation generally use samples distributed evenly in the parameter space. A methodology to specify the desired result envelope and perform the minimum number of experiments required to discover the corresponding process parameters is not evident in the literature. Such a procedure would be particularly novel if it could make use of historical data to interpolate new scenarios (eg. predicting the behaviour of a new alloy / additive combination).

7.1.2 Innovation

In-Situ AAO Sensor

AAO sensors have been demonstrated in the lab but are not widely available to industry. White-light interferometry and AC impedance spectroscopy are particularly promising non-contact technologies with a potential for low-cost implementations.

A functional AAO sensor would eliminate the need to place test pieces in a batch and enable exact determination of anodisation run-times.

Current Density Calculation

Potentiostatically controlled anodisation can be considered 'self-regulating' because the current density is defined by the voltage and surface area - the job will draw as much or as little current as required (assuming that the demands are within the power supply system's limit).

Current density is a critical predictor of anodic film properties and could be calculated if the voltage, current and cathode surface area are known. Although many anodisation rectifier systems will record I-V traces this information is often silo-ed.

A retrofit system and accompanying algorithm to calculate anodisation current density in real-time would provide a valuable piece of information to anodisation operators.

Low-Cost Tank Monitoring / Auto-Dosing Systems

Anodisation tank auto-dosing systems exist however they are not commercially viable for the majority of operators. Sensors to continuously monitor tank electrolyte are also available but are generally not installed because samples can be taken manually when the tank is being maintained. Digitalisation of anodisation will increase demand for online sensors and full auto-dosing systems.

Accessibly priced online electrolyte sensors (or full auto-dosing systems) will reduce labour requirements, increase the consistency of tank parameters and may enable auto-compensation for out-of-envelope conditions.

8 References

[1] "Anolok Bronze Anodising." [Online]. Available: https://www.unitedanodisers.com/index.php/about-anodising/anolok-trade-bronze-anodising.html. [Accessed: 06-Sep-2021].

[2] M. P. Martínez-Viademonte, S. T. Abrahami, T. Hack, M. Burchardt, and H. Terryn, "A review on anodizing of aerospace aluminum alloys for corrosion protection," *Coatings*, vol. 10, no. 11, pp. 1–30, 2020.

[3] "Aluminum Anodizers Council." [Online]. Available: https://www.anodizing.org/. [Accessed: 23-Aug-2021].

[4] J. Tafel, "Über die Polarisation bei kathodischer Wasserstoffentwicklung," *Zeitschrift für Phys. Chemie*, vol. 50U, no. 1, pp. 641–712, Nov. 1905.

[5] P. L. Robinson, "Gmelins Handbuch Der Anorganischen Chemie. 8th ed. Edited by the German Chemical Society. System-Nummer 35: Aluminium. Teil A-Lieferung 1. Pp. iv + 284. Berlin: Verlag Chemie, 1934," *J. Soc. Chem. Ind.*, vol. 54, no. 16, pp. 357–357, Apr. 1935.

[6] F. Keller, M. S. Hunter, and D. L. Robinson, "Structural Features of Oxide Coatings on Aluminum," *J. Electrochem. Soc.*, vol. 100, no. 9, p. 411, 1953.

[7] P. G. Sheasby and R. Pinner, *The Surface Treatment and Finishing of Aluminum and Its Alloys, 6th Edition*. 2001.

[8] J. M. Runge and A. J. Pomis, "Anodic Oxide Film Formation Relating Mechanism to Composition and Structure," in *AESF SUR/FIN*, 2000, pp. 266–277.

[9] M. Lerner, "Is the barrier layer responsible for the cellular structure of aluminum oxide film anodized in sulfuric acid," *Proc. AESF Surfin Conf. Chicago*, pp. 139–149, 2003.

[10] S. J. Garcia-Vergara, L. Iglesias-Rubianes, C. E. Blanco-Pinzon, P. Skeldon, G. E. Thompson, and P. Campestrini, "Mechanical instability and pore generation in anodic alumina," *Proc. R. Soc. A Math. Phys. Eng. Sci.*, vol. 462, no. 2072, pp. 2345–2358, 2006.

[11] L. Wen, R. Xu, Y. Mi, and Y. Lei, "Multiple nanostructures based on anodized aluminium oxide templates," *Nat. Nanotechnol.*, vol. 12, no. 3, pp. 244–250, 2017.

[12] J. M. Runge, *The metallurgy of anodizing aluminum: Connecting science to practice*. 2018.

[13] J. M. Runge, "A Brief History of Anodizing Aluminum," in *The Metallurgy of Anodizing Aluminum*, Cham: Springer International Publishing, 2018, pp. 65–148.

[14] A. Brace, "The technology of anodizing aluminum, third edition," *Met. Finish.*, vol. 98, no. 6, p. 611, Jan. 2000.

[15] K. H. Rashid, A. A. Khadom, and H. B. Mahood, "Aluminum ASA 6061 Anodizing Process by Chromic Acid Using Box–Wilson Central Composite Design: Optimization and Corrosion Tendency," *Met. Mater. Int.*, no. 123456789, 2020.

[16] M. Z. Mubarok, Wahab, Sutarno, and S. Wahyudi, "Effects of Anodizing Parameters in Tartaric-Sulphuric Acid on Coating Thickness and Corrosion Resistance of Al 2024 T3 Alloy," *J. Miner. Mater. Charact. Eng.*, vol. 3, no. 3, pp. 154–163, 2015.

[17] R. Akolkar, U. Landau, H. Kuo, and Y. M. Wang, "Modeling of the current distribution in aluminum anodization," *J. Appl. Electrochem.*, vol. 34, no. 8, pp. 807–813, 2004.

[18] S. J. Garcia-Vergara, P. Skeldon, G. E. Thompson, and H. Habazaki, "A flow model of porous anodic film growth on aluminium," *Electrochim. Acta*, vol. 52, no. 2, pp. 681–687, 2006.

[19] J. E. Houser and K. R. Hebert, “The role of viscous flow of oxide in the growth of self-ordered porous anodic alumina films,” *Nat. Mater.*, vol. 8, no. 5, pp. 415–420, 2009.

[20] J. M. Runge, *Anodizing as an Industrial Process*. 2018.

[21] M. R. Deakin and O. R. Melroy, “Monitoring the Growth of an Oxide Film on Aluminum In Situ with the Quartz Crystal Microbalance,” *J. Electrochem. Soc.*, vol. 136, no. 2, pp. 349–352, 1989.

[22] E. K. Lindmark, J. J. Nowak, and M. T. Kief, “In-situ ellipsometric measurements of thin film aluminum oxidation,” *Opt. Metrol. Roadmap Semicond. Opt. Data Storage Ind.*, vol. 4099, no. September, p. 218, 2000.

[23] K. Habib, “AC impedance-emission spectroscopy for determining the electrochemical behaviour of anodised aluminium in aqueous solutions,” *Nondestruct. Test. Eval.*, vol. 25, no. 3, pp. 181–188, 2010.

[24] D. Veys-Renaux, N. Chahboun, and E. Rocca, “Anodizing of multiphase aluminium alloys in sulfuric acid: in-situ electrochemical behaviour and oxide properties,” *Electrochim. Acta*, vol. 211, pp. 1056–1065, 2016.

[25] S. S. Lee, S. K. Sun, and K. J. Kang, “In-situ measurement of the thickness of aluminum oxide scales at high temperature,” *Oxid. Met.*, vol. 63, no. 1–2, pp. 73–85, 2005.

[26] F. Karim, T. Bora, M. Chaudhari, K. Habib, W. Mohammed, and J. Dutta, “Measurement of aluminum oxide film by Fabry–Pérot interferometry and scanning electron microscopy,” *J. Saudi Chem. Soc.*, vol. 21, no. 8, pp. 938–942, 2017.

[27] A. D. Juhl, K. Burfelt, and P. Weldingh, “Saving energy in a conventional anodizing line using pulse instead of direct current on aluminum profiles at Sapa, Denmark,” *Light Met. Age*, vol. 66, no. 3, pp. 26–28, 2008.

[28] A. D. Juhl, “Why it makes sense to upgrade to pulse anodizing,” *Met. Finish.*, vol. 107, no. 7–8, pp. 24–27, Jul. 2009.

[29] A. D. Juhl, P. D, and M. Sc, “Pulse Anodizing in an Existing Anodizing Line,” *Current*, vol. 2, pp. 1–5, 1970.

[30] H. Derhamy, J. Eliasson, J. Delsing, and P. Priller, “A survey of commercial frameworks for the Internet of Things,” in *2015 IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA)*, 2015, pp. 1–8.