EXTENDED ESSAY

-Chemistry-

Investigation of the Effect of Voltage on Anodizing Aluminum

How does the voltage affect the amount of Al_2O_3 produced and the quality of the oxide finish while anodizing aluminum determined by mass comparisons and coloring at 25.0 ^{0}C and 1.00 atm?

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CONTENTS

INTRODUCTION

Anodizing is an electrochemical process of oxidation in an acidic electrolyte bath. Anodizable metals react with the oxygen in the air and so, under natural conditions, always have a thin oxide film on the surface. When anodized, the thickness of the naturally existing barrier oxide increases, creating an anodic oxide finish which, depending on the process, can form the hardest substance known after diamonds.

Anodizing, as opposed to bare metal, improves corrosion resistance and offers a stronger bond for paint primers and glues. It is also used to create dielectric films for electrolytic capacitors and to avoid galling of threaded parts.

The process basically consists of electrically depositing an oxide film from an aqueous solution onto the surface of a metal, serving as the anode in the electrolytic cell. The properties of the finish depend on type, concentration and temperature of the electrolyte, the treatment time, the strength of the current and the voltage introduced to the electrolyte and the metal used. The metal used in the anodizing process is preferred to be nonferrous.

This process is not a useful treatment for ferrous metals such as iron or carbon steel because these metals exfoliate when oxidized; i.e. the iron oxide, flakes off, constantly exposing the underlying metal to corrosion.

Anodizing changes the texture of the surface and also changes the crystal structure of the metal near the surface. Thick coatings are normally porous, so a sealing process is often needed to achieve corrosion resistance.

RESEARCH QUESTION

How does the voltage affect the amount of Al_2O_3 produced and the quality of the oxide finish while anodizing aluminum determined by mass comparisons and coloring at 25.0 ºC and 1.00 atm?

BACKGROUND INFORMATION

Aluminum Anodizing

An oxide film can be grown on various metals such as; aluminum, niobium, tantalum, titanium, tungsten, zirconium, by anodizing. Aluminum differs from the other metals in that, in addition to the thin oxide layer it also produces a thick oxide coating containing a high density of microscopic pores.

In an anodizing cell, the aluminum is connected to the positive terminal of the power supply and is made the anode. The cathode, which is a plate or rod of any electronic conductor that is unreactive in the anodizing bath such as carbon, lead, nickel or stainless steel, is connected to the negative terminal of the supply. When the process starts, electrons are withdrawn from the metal at the positive terminal, allowing ions at the metal surface to react with water to form an oxide layer on the metal. The electrons return to the bath at the cathode where they react with hydrogen ions to produce hydrogen gas.

Another differentiator of aluminum is that both barrier and porous oxides can be grown on it. Barrier oxides grow in near neutral solutions in which aluminum oxide is hardly soluble, most commonly ammonium borate, phosphate, or tartrate compositions. It stabilizes the surface against further reactions with its environment and is an excellent choice for electrical insulators.

When the current is flowing in the cell, sulfuric acid begins to decompose and the hydrogen ions move to the cathode where they are reduced to hydrogen gas:

$$2H^+_{(aq)} + 2e^- \longrightarrow H_{2(g)}$$

Simultaneously, negatively charged anions move to the anode. The electrical charge in the circuit causes positively charged aluminum ions (Al^{3+}) to be generated in the anode and in turn, move towards the cathode. At the anode surface they react with the oxide/hydroxide ions to form aluminum oxide. H^+ can be at high concentration near the oxide layer due to the anode reactions.

Electrochemical reactions at the anode

$$Al_{(s)} \longrightarrow Al^{3+}_{(aq)} + 3e^-$$

$$2Al^{3+}_{(aq)} + 3O^{2-}_{(aq)} \longrightarrow Al_2O_{3(s)}$$

$2Al^{3+}_{(aq)} + 3OH^-_{(aq)} \longrightarrow Al_2O_{3(s)} + 3H^+_{(aq)}$ for which the overall process is;

$$2Al_{(s)} + 3H_2O_{(l)} \longrightarrow Al_2O_{3(s)} + 6H^+_{(aq)} + 6e^-$$

Electrochemical reactions at the cathode

$$6H^+_{(aq)} + 6e^- \longrightarrow 3H_{2(g)}$$

The oxide coating contains 12 – 15% sulfate ions which facilitate the movement of hydrogen ions reducing the cell voltages required.

Aluminum oxide is formed when fresh aluminum reacts with oxygen. If shaped, the oxide forms an impenetrable layer that is tightly bound to the surface. As a result, further reaction is halted. Despite its tenacity, the film is very thin and can be removed by abrasion and chemical corrosion. When this happens, the aluminum will wear or the surface will mark or become pitted at the site of corrosion.

The oxide layer produced during the early stages of anodizing is dense and uniform. It is known as the barrier layer because it offers the greatest resistance to wear and corrosion. When the high electrical resistance of the oxide decreases the potential of the applied voltage in the electrolytic cell, the growth of this layer stops. Subsequent growth is very slow and competes with the acid reaction:

$$Al_2O_{3(s)} + 6H^+_{(aq)} \longrightarrow 2Al^{3+}(aq) + 3H_2O_{(l)}$$

which releases Al^{3+} ions into the solution.

Resulting anodizing reaction

$$2Al_{(s)} + 3H_2O_{(l)} \longrightarrow Al_2O_{3(s)} + 3H_{2(g)}$$

In aqueous solutions aluminum oxide may form various hydrates;

$$Al_2O_3 \times (H_2O)_n,\ n=1 \text{ to } 3$$

The oxide formed has a hexagonal cellular structure, with each cell containing a central pore. Most anodization conditions create films with more disorder, with a distribution of cell size and pore diameter. The size of the cells and pores varies depending on the bath composition, temperature, and voltage, but the end result is always a dense network of fine pores.

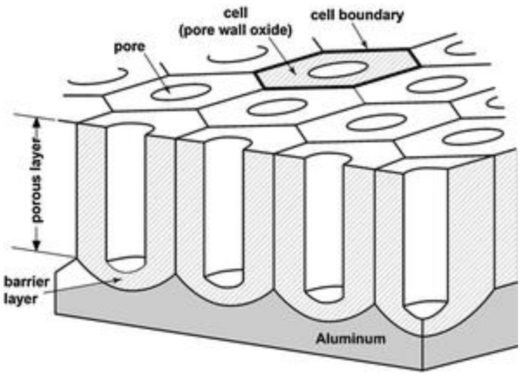


Figure 1. Schematic illustration of the structure of a porous anodic aluminum oxide

This porous structure allows the oxide finished to be dyed. After anodizing, the pores are empty. Therefore, in case of coloring, dye particles are to be absorbed by the pores and integrated onto the surface of the finish.

By boiling after the dye has soaked in, or dying using a color bath as a sealing solution for about 20 minutes to an hour will close the pores and seal the color in. Even tough industry-made dyes are the first choice for this process, fabric dyes in dust form are also used, mainly for in-home anodizing.

Types of Anodizing

There are three types of aluminum anodizing; Type I, II and III. Type I, also known as chromic acid anodizing, produces the thinnest oxide layer of all types, approximately 0.51 to 2.54 microns per surface. Even though it is very thin, this oxide layer is very resistant to corrosion and so, is used for the treatment of aircraft components. This type of anodizing was the one used in the first commercial anodizing process invented in 1923 by Bengough and Stuart. The film appears in an opaque gray color and absorbs very little color when dyed, which limits its decorative uses. With chromic acid being carcinogenic, mutagenic and incredibly toxic, this type of anodizing is done on industrial scale with the appropriate safety measures.

Type II anodizing, also known as sulfuric acid anodizing, produces a semi-transparent colorless film up to 35 microns in thickness. The film produced is suitable for both decorative and corrosion-resistant applications.

Type III anodizing is done in a sulfuric acid bath at low temperatures, usually between -5ºC and 5ºC. The sulfuric acid bath has reduced activity and so the oxide layer grows thicker than in type II. The film produced is extremely hard and durable and so is preferred in engineering.

HYPOTHESIS

As the voltage increases, the amount of Al_2O_3 produced is expected to increase and so, the quality of the oxide finish. The reason behind this hypothesis is that in past research it has been observed that pore density decreases, resulting in an increase in pore sizes, enabling more current to go through each pore. This dissolution of pores increases rate of Al_2O_3 production. The more Al_2O_3 produced, the stronger the layer will be against corrosion and the color will hold better.

H1: There is statistically significant mean difference between the amount of Al_2O_3 produced with different voltages of anodizing.

H0: There isn't any statistically significant mean difference between the amount of Al_2O_3 produced with different voltages of anodizing.

PRELIMINARY TESTING

During the preliminary testing, many problems were faced. After conducting many trials, the method was perfected. In the first trial, an aluminum plate with the measurements of 5.7cm and 14.8cm was used as the cathode. Outlet of hydrogen gas was observed. However, no change in mass could be recorded. Therefore, the cathode was changed to lead.

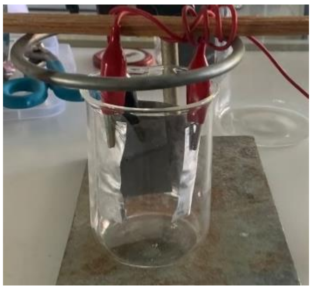


Figure 2. set up of aluminum cathode anodizing

Within the next trials, the reaction could not be started, which then was related to the copper wires not being able to conduct the current, presumed to be because of loose contact. The setup was rearranged to connect the current directly to the anode and cathodes.

Figure 3. set up without copper wires

Many different voltage values were experimented with to decide upon a range. Minimum voltage tried was 3.0V, which resulted in close to none aluminum oxide production. No change in mass was recorded and the paint didn't hold. Maximum voltage tried was 17.1V; the aluminum burned and broke into two pieces in the time stamp 5.40. Despite no accurate measurements in mass could be made, great amount of aluminum oxide production could be observed after coloring.

Figure 4. dyed aluminum piece anodized at V=17.1V

METHODOLOGY

Variables

Variable type	**Variable**	**Explanation**
Independent Variable(s)	Voltage used to anodize aluminum	Determined through the voltmeter on the power supply.
Dependent Variable(s)	Amount of Al_2O_3 produced	Measured through the calculation of change in mass by the extraction of initial mass from final mass with the use of an accurate electronic balance.
	Current	As the same metal and solution were used in all trials, the resistance was constant. As can be seen through the formula $V = I \times R$, change in voltage directly causes the current to change. The

		current was measured through the amperemeter on the power supply.
Controlled Variable(s)	Anodizing solution	Sulphuric acid solution with 2M concentration and volume of 182.5 ± 0.05 mL was used in each trial.
	Temperature	The trials are conducted in the same lab with room temperature of 25.0 ± 0.5 Cº.
	Type of anodizing	Type II anodizing method was conducted in all trials.
	Anodized metal	Aluminum pieces with measurements of 4.96 ± 0.05cm to 3.01 ± 0.05cm were used. Pieces were cut from the same aluminum sheet.
	Dye used to color anodized aluminum pieces	All aluminum pieces were dyed in the same dye bath, prepared with the identical dye packages.
	Cathode used in the circuit	Identical lead pieces with measurements of 10.45 ± 0.05cm to 4.07 ± 0.05cm were used as cathodes in each trial.

	Time of anodizing	Aluminum pieces were all anodized for 20.0 ± 0.2 minutes.

Table 1. Variables of experiment

Apparatus

30 cm ruler (±0.05cm)

50mL graduated cylinder (±0.05mL)

100mL graduated cylinder (±0.05mL)

80mL beaker (±0.05mL)

150mL beaker (±0.05mL)

Lead plates with measurements of 10.45 ± 0.05cm to 4.07 ± 0.05cm

Power supply with voltmeter (±0.1V) and amperemeter (±0.01A)

Tweezers

Sandpaper

Funnel

Stopwatch (±0.2s)

Electronic balance (±0.001g)

Paper towels

25x aluminum plates with measurements of 4.96 ± 0.05cm to 3.01 ± 0.05cm

Wires and crocodile clips

Cattle

Stirring rod

Chemicals

Per anodizing:

40mL 5M Sodium Hydroxide ($NaOH$)

182.5mL 2M Sulphuric Acid (H_2SO_4)

1 package of powder fabric dye

Note: Acid and lead are reused for multiple trials.

Method

Preparation and cleaning of aluminum in order the remove the already existing oxide layer.

1) Cut the aluminum to fit the measurements of 4.96 ± 0.05 cm to 3.01 ± 0.05 cm.

2) Rub both sides of the aluminum with sandpaper for 1-2 minutes until able to visually observe change. You should obtain a smooth and bright aluminum sheet.

3) Measure 40mL of 5M NaOH solution with a graduated cylinder. This step should take place in a fume cupboard for safety reasons. (see safety instructions for further information)

4) Using a funnel, transfer the NaOH into a beaker from the graduated cylinder.

5) Put the aluminum into the bottom of the solution and etch for 6 minutes. You should be able to visually observe the exit of gas bubbles as a sign of the oxide layer degenerating.

6) Remove the aluminum using tweezers and gently dry it with a paper towel until fully dry.

7) Rinse it with warm water (43.3 to 32.2 C⁰) and gently dry it with a paper towel until fully dry.

8) Accurately weigh the aluminum piece and record the data in grams.

9) Draw a graph of voltage vs. increase in mass through the recorded data in Step 8 to comment on the relationship.

Preparation of the anodizing bath

1) Fill a beaker with 182.5mL of 2M sulphuric acid.

2) Set up the anodizing power supply circuit as shown at the diagram below;

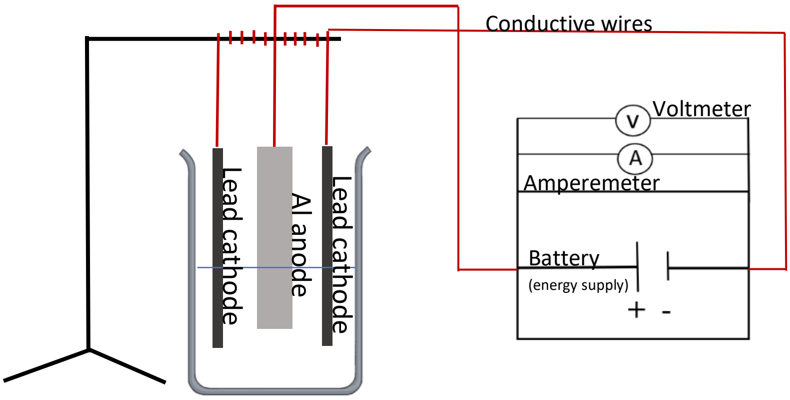


Figure 5. diagram of the anodizing setup

Preparation of the dying bath

1) Heat water in cattle.

2) Fill 240mL of a beaker with hot water by using a graduated cylinder.

3) Mix in the powder fabric dye until the color of the dye fully sets in the water using a stirring rod.

Anodizing and dying aluminum

1) Set up the power supply to the desired value of voltage (4.7V, 6.5V, 10.6V, 13.0V, 14.5V respectively).

2) Connect the two lead plates to the negative end of the power supply, make sure they are not in contact with each other or the glass.

3) Place the aluminum to stay in-between the lead plates, with no contact to them and connect to the positive end of the power supply by using crocodile.

4) Wait for 20 minutes by following the time using the stopwatch.

5) Remove the aluminum with the tweezer and gently dry it with a paper towel.

6) Accurately weigh the aluminum by using the electronic balance and record the data.

7) Place it in the dying bath.

8) Remove after 20 minutes of being soaked in the dying bath.

9) Let it dry for 15 minutes or more.

Repeat for each voltage value (4.7V, 6.5V, 10.6V, 13.0V, 14.5V), for five times each.

Safety Instructions

1) Wear gloves, safety googles and a lab coat at all times while conducting the experiment since the chemicals used (NaOH, H_2SO_4) are corrosive and irritant.

a. If any chemicals are to come into contact with the skin, rinse thoroughly with cold water.

b. If any chemicals are to come into contact with the eyes, rinse for several minutes and call a doctor.

2) Carry out all etching and anodizing steps in a fume cupboard as the hydrogen gas that will evolve from those steps is highly flammable and explosive.

3) Do not allow any material near your mouth, nose or eyes to stop any hazardous material to go into your system.

4) Do not let lead cathodes come into contact with your skin since it can be slightly hazardous.

a. If to come into contact with the skin, rinse thoroughly with cold water.

5) When the power supply is on, make sure not to come into contact with any conductive material connected to the power supply.

a. In case of an electric shock, immediately call a doctor.

Waste and Disposal

1) Be sure to not spill or throw away any waste into all-purpose bins as they will be toxic for the environment. Dispose all into a chemical waste bin.

2) Do not mix acids and bases and keep away from metals when not used in the experiment.

a. In case of a spillage, neutralize and clean up the area immediately.

DATA COLLECTION

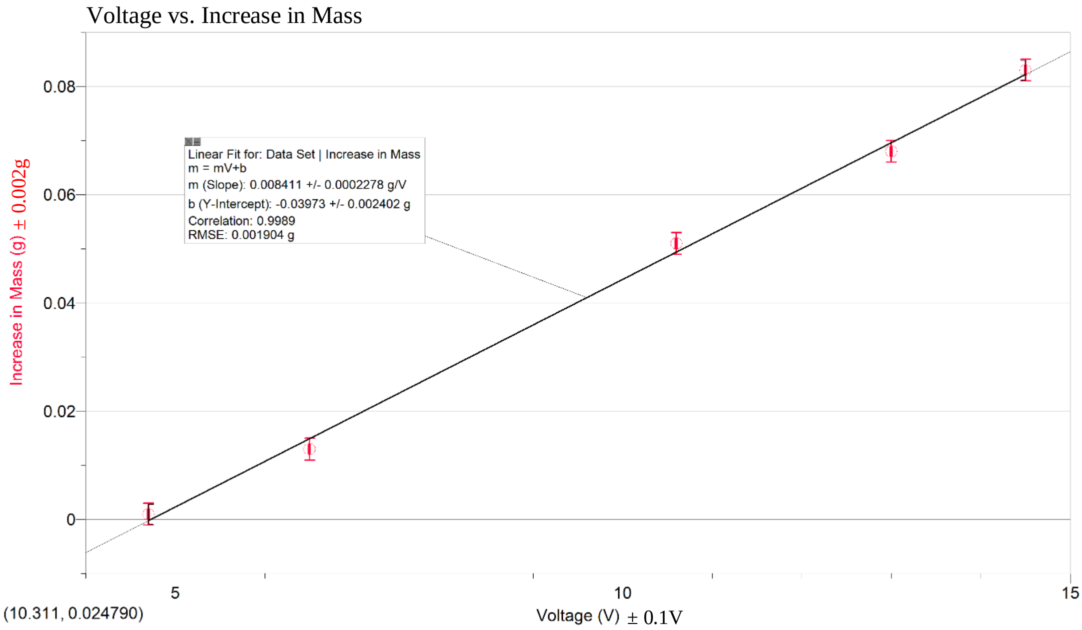
In this section, the results of the experiment will be displayed graphically and explained through analysis of data.

Raw Data

Voltage (±0.1V)	**Current (±0.01A)**	**Initial mass (±0.001g)**	**Final mass (±0.001g)**	**Increase in mass (±0.002g)**	**Average change in mass (±0.002g)**
4.7V	0.05	0.558	0.559	0.001	0.001
	0.05	0.532	0.535	0.003	
	0.05	0.603	0.604	0.001	
	0.05	0.596	0.597	0.001	
	0.05	0.588	0.590	0.002	
6.5V	0.07	0.600	0.614	0.014	0.013
	0.07	0.608	0.619	0.011	
	0.07	0.597	0.614	0.017	
	0.07	0.602	0.6 11	0.009	
	0.07	0.570	0.586	0.016	
10.6V	0.11	0.520	0.573	0.053	0.051
	0.11	0.583	0.629	0.046	
	0.11	0.562	0.611	0.049	
	0.11	0.531	0.588	0.057	
	0.11	0.547	0.598	0.051	
13.0V	0.14	0.608	0.664	0.056	0.068
	0.14	0.601	0.682	0.081	
	0.14	0.613	0.682	0.069	
	0.14	0.639	0.707	0.053	
	0.14	0.596	0.679	0.083	
14.5V	0.15	0.615	0.701	0.086	0.083
	0.15	0.617	0.696	0.079	
	0.15	0.629	0.710	0.081	
	0.15	0.636	0.720	0.084	
	0.15	0.618	0.705	0.087	

Table 2. Data collected from all trials and their averages.

In order to analyze the results, a graph was drawn to display the increase in mass against voltage values. The errors integrated into the error bars in the above measurement are from the voltage values (±0.1V) and the mass of aluminum plates (±0.001g) which when calculated into change in mass is multiplied by two, due to the rules of uncertainty calculations. The y-axis error for each data point was found to be ±0.002g and is shown on each point as y-error bars. The x-axis error for each data point was found to be ±0.1V and is shown on each point as x-error bars.



Graph 1. Graph showing increase in mass against voltage with a linear line of best fit

Thus, the linear relationship between anodizing voltage and oxide layer production can be seen through the graph and the hypothesis is supported by the experimental results.

Theoretical Oxide Layer Production

A common equation called the “312 rule” is used in the industry to mainly calculate specific anodizing time needed for certain thicknesses of oxide layers when type II anodizing;

$$minutes\ to\ anodize = \frac{microns\ of\ coating\ desired \times 3.12}{amperes\ per\ square\ decimeter}$$

$$t = \frac{\mu m \times 3.12}{{}^{I}/_{dm^2}} \text{ where,}$$

$$\frac{I}{dm^2} = current\ density$$

This can be rewritten to fit the experiment as;

$$\mu m = \frac{t \times I/dm^2}{3.12}$$

As due to the equation $V = I \times R$, the current increases directly proportionally to voltage, the currents can be used for the calculations. This formula, therefore, suggests a linear relationship.

$$area\ of\ aluminum\ plates = (4.96\ \pm\ 0.05\text{cm})\ \times (3.01\ \pm\ 0.05\text{cm})$$

The uncertainties of the length measurements are turned into percentage uncertainties as follows;

$$\%uncertainty = \frac{0.05\times100}{4.96} = 1.008\% \approx 1\%\ (1\ \text{s.f.})$$

$$\%uncertainty = \frac{0.05 \times 100}{3.01} = 1.661\% \approx 2\%\ (1\ \text{s.f.})$$

Therefore, the area of the aluminum plates is calculated as;

$$Area =\ (4.96\ \pm\ 1.0\%)\text{cm}\ \times (3.01\ \pm 2\%)cm$$

In which, the multiplied values are multiplied with 0.1 to convert into decimeters.

$$Area = (0.496\ \pm\ 1.0\%)\text{dm}\ \times (0.301\ \pm 2\%)dm$$

$$\approx 0.149 \pm 3\%\ dm^2$$

This value is then used to calculate the current density for each value. (example calculation is done using $\text{V} =\ 4.7\text{V}$)

For $\text{V} =\ 4.7\text{V}$, we have a current of $I = 0.05\ \pm 0.01$ which equals $I = 0.05\ \pm 20\%$ when turned into percentage uncertainty.

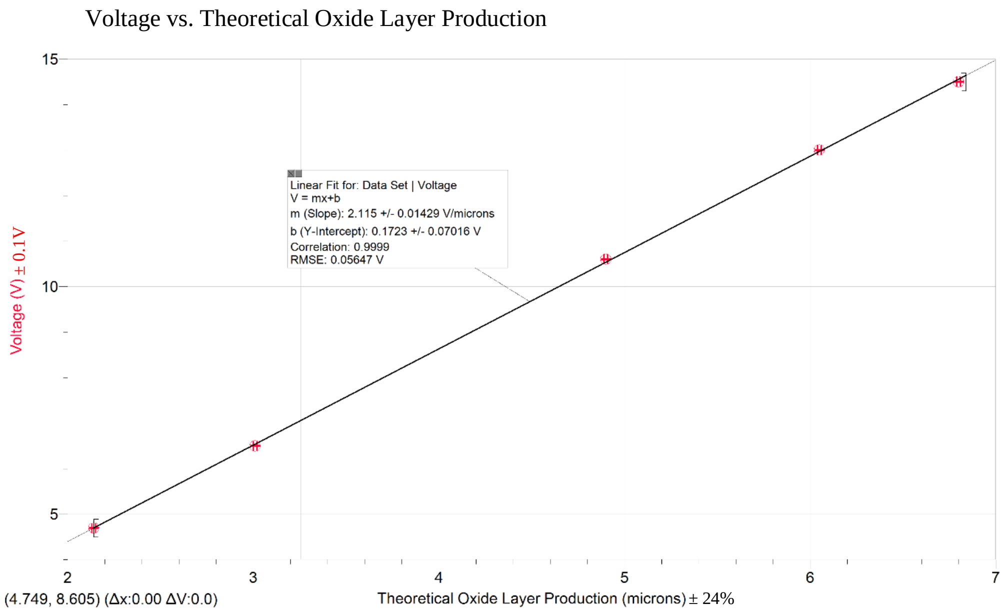
$$current\ density = \frac{0.05\pm20\%}{0.149\pm3\%}$$

$$\approx 0.336 \pm 23\%\ \ (2\ \text{s.f.})$$

Then, put into the “312 rule” equation, the theoretical oxide layer production can be calculated.

$$\mu m = \frac{(20.0\pm1\%)\times(0.336\pm23\%)}{3.12} = \frac{6.67\pm24\%}{3.12}$$

$$\approx 2.15 \pm 24\%\ \mu m$$



Graph 2. Graph showing the theoretical oxide layer production with each voltage value.

To be able to directly compare the theoretical and experimental values, we must convert them into the same type of measure. For that we use the equation given below;

$$thickness = \frac{Volume}{area}$$

which when rewritten, gives us;

$$thickness = \frac{{}^{mass}/_{density}}{area}$$

(where thickness in centimeters, mass in grams, density in g/cm^3, area in cm^2)

The theoretical mass production values can be calculated as follows; (example calculation is done using V = 4.7V value)

$$\text{For V} = 4.7\text{V}, thickness = 2.15 \pm 24\% \ \mu m.$$

$$\frac{2.15 \pm 24\% \ \mu m}{10000} = \frac{mass/3.95}{14.9 \pm 3\%}$$

$$\frac{32.0 \pm 27\%}{10000} = \frac{mass}{3.95}$$

$$mass = 0.0126 \pm 27\% \ \text{g}$$

(The theoretical mass production values for all voltages can be found in Table 3.)

Data Comparison and Processing

By comparing the theoretical oxide layer production with the raw data, both the accuracy of the results and the formula leading to the theoretical data, and how big of errors were possibly made during the experiment can be determined. For this, percentage error is calculated using the following equation;

$$percentage\ error = \frac{|experimental\ value - theoretical\ value|}{theoretical\ value} \times 100$$

When compared with percentage uncertainty, which is used to quantitively express the precision of measures, it can be decided if there was a systematic error or not.

Example calculation of percentage error for voltage value $\mathrm{V} = 4.7\mathrm{V}$;

$$\frac{|0.001 - 0.0126|}{0.0126} \times 100 = 92\%$$

Detailed evaluation of the data provided in Table 3 can be found under Error Analysis.

Voltage (±0.1V)	**Average Increase in Mass (±0.002g)**	**Theoretical Oxide Layer Production (±0.001g)**	**Percentage Uncertainty**	**Percentage Error**
4.7	0.001	0.0126	27%	92%
6.5	0.013	0.0211	21%	86%
10.6	0.051	0.0279	16%	83%
13.0	0.068	0.0354	14%	92%
14.5	0.083	0.0380	14%	94%

Table 3. Theoretical and actual data comparison with error and uncertainty results

Qualitative Data (Color Comparison)

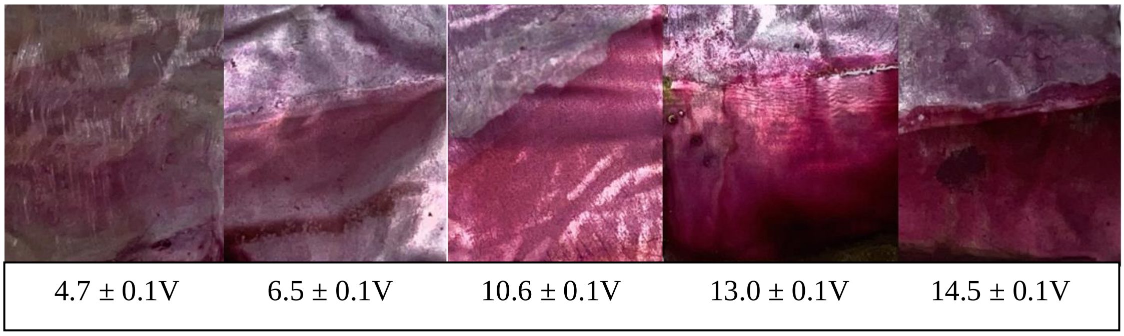


Figure 6. Colored aluminum plates anodized in increasing voltage respectively

With being left in the coloring bath and hanged out to dry for the same amount of time, the sample plates' colors can be directly compared to gain qualitative data. As the porous structure is expected to gain volume with increasing production of the oxide layer, more anodized plates are expected to hold more dye. Less anodized plated on the other hand would hold little dye and the rest would wash off. Therefore, it can be determined by whether the color is clearer and stronger or faded.

Plates used in the first trial of the experiment can be seen in Figure 6. It is clear to the eye that the color is held better in higher voltages while it is close to none in smaller voltages. This suggests more Al_2O_3 was produced with increasing voltage, supporting the initial hypothesis.

CONCLUSION

The research question for this investigation is;

How does the voltage affect the amount of Al_2O_3 produced and the quality of the oxide finish while anodizing aluminum determined by mass comparisons and coloring at 25.0°C and 1.00 atm?

Anodized aluminum can be found in various areas in our daily lives from microwave ovens in our kitchens to our window frames. Such a wide range of applications for anodized aluminum makes it crucial to obtain the most efficient production process. Discovering the relationship between voltage and the aluminum oxide produced will enable the industry to work with optimum voltage, increasing efficiency.

On this background, I aimed to find the relationship between anodizing voltage and the quality and quantity of the aluminum oxide produced in this experiment. The results were obtained by conducting an experiment where five different voltage values were employed for five trials each to lower the error, and the experimental and theoretical results were compared with percentage error.

As indicated by the results presented in the Data Collection section of this essay, both the experimental and theoretical data conclude that there is a linear relationship between anodizing voltage and the amount of Al_2O_3 produced with 20 minutes of anodizing time. This linear relationship is as shown in graphs 1 and 2 in the previous section.

It can also be appointed that the color was held better with increasing voltages, suggesting that the quality of the oxide finish also increases as more Al_2O_3 is produced. The implication of the data received through the experiment is that the ideal voltage to anodize aluminum is between the range of 13.0V to 15.0V.

EVALUATION

Error Analysis

As it can be seen from the variance of data of the above graphs (the points lying outside the line of best fit), there are errors inherent in the experiment.

When looked at Graph 1, variance of data is in both directions of the line of best fit above and under, suggesting the existence of minor random error rather than a systematic one.

Minor random errors might have occurred while measuring the time (anodizing, etching, dying) due to the imperfection of human reaction. However, it is accepted to have little or no significant effect on the results, and therefore, is not accounted for.

The biggest source of random errors is possibly the different positioning of samples on the electronic balance each time. The electronic balance is an extremely sensitive instrument, affected even by the position of the person. Therefore, it could have led to errors in measurement. These random errors can be minimized with increasing the amount of trials.

As calculated in Data Comparison and Processing, with the percentage error being bigger than percentage uncertainty in all voltage values, there is systematic error in the investigation which can be stated as being the biggest source of error in the experiment.

The two possible sources of this can identified as instrumental and environmental factors. An imperfect calibration of the electronic balance would lead to imperfect reading with deflections close to each other. This can be avoided with using a pre-checked instrument known to be giving correct reading. Also, in case of the amperemeter giving wrong reading, the theoretical value would be calculated wrong. This can again be avoided by using another instrument or by calculating the current through $V = I \times R$ by measuring the resistance and comparing with the value read in the amperemeter. Resistance also varies with temperature. In an ongoing electrochemical reaction, heat is generated, and therefore, the resistance of the wires increases.

Also, the theoretical value doesn’t consider neither the possibility of the aluminum sheets reacting with the oxygen in the atmosphere, producing more aluminum oxide in the meantime nor some amount of loss of mass during the anodization due to the degeneration of aluminum in sulphuric acid.

Aside from all this, taking the qualitative color comparisons and the results being found as being linear into consideration, it can be stated that the difference between the theoretical and the experimental data does not change conclusion of 13.0V to 15.0V being ideal for anodizing aluminum.

Further Investigation and Improvements

One issue with the experiment was the choice of measure. The oxide layer itself is extremely thin and cannot be measured conventionally with a micrometer or any other measuring device. Therefore, conversions and inferences are made. Even though theoretically there are no issues, due to the high amount of calculations, the uncertainties accelerate and decrease the accuracy of the results. Also, the significant property of the pores being able to absorb paint could only be used as a qualitative data. In order to increase accuracy and deduce the risk of errors in calculation, colorimeter could be used to determine the oxide layer thickness. It would create quantitative data through the absorbance property of the oxide finish while also being an easy and simple method.

With its high use in industry and little research conducted on the topic, many further investigations on aluminum anodizing can be produced. Rather than the effect of voltage, the effect of concentration, time or temperature on the quality of the oxide finish in order to determine ideal values.

Also, the experiment can be conducted using other types of metals anodized in industrial use, such as zinc, titanium, niobium, etc. Comparisons between the quality of the oxide finish against corrosion or by how well they hold paint can be used to determine the ideal metal of choice for anodizing.

BIBLIOGRAPHY

Alwitt, Robert S. *The Electrochemical Society*. December 2002. https://knowledge.electrochem.org/encycl/art-a02-anodizing.htm. 2021.

Bouchama, L. "Enhancing aluminum corrosion resistance by two-step anodizing process." *Elsevier* (2013).

Chesterfield, Larry. Calculating Anodizing Rate for Type II and Type III Coatings. 01 August 2008. *https://www.pfonline.com/articles/calculating-anodizing-rate-for-type-ii-and-type-iii-coatings*. 2021.

D.E.Boldrini. "INFLUENCE OF THE ANODIZING PROCESS VARIABLES ON THE ACIDIC PROPERTIES OF ." *Brazilian Journal of Chemical Engineering* (2017).

Emmanuel, Delphine Veys-Renaux Najat Chahboun. "Anodizing of multiphase aluminium alloys in sulfuric acid: in-situ electrochemical behaviour and oxide properties." *Electrochimica Acta* (2016).

"Factors Affecting The Anodizing Of An Aluminum Metal." *UKEssays* (2018).

finishing.com. Intro to Anodizing of Aluminum. *https://www.finishing.com/faqs/anodizing.shtml*. n.d. 2021.

Gordeeva, Elena O. "Aluminium anodizing in selenic acid: electrochemical behaviour, porous structure, and ordering regimes." *Lomonosov Moscow State University* (2019).

Henley, V F. *Anodic Oxidation of Aluminium and Its Alloys*. Pergamon Press Ltd, 1082.

Praxier Material Safety Sheet. July 2007. http://dept.harpercollege.edu/chemistry/msds/Hydrogen%20Compressed%20Gas%20Praxair.pdf.

"Safety Data Sheet; Sufuric Acid." 15 02 2015. *https://beta-static.fishersci.com/content/dam/fishersci/en_US/documents/programs/education/regulatory-documents/sds/chemicals/chemicals-s/S25899.pdf.* 2021.

Lin, Yuanjing. "A Highly Controllable Electrochemical Anodization Process to Fabricate Porous Anodic Aluminum Oxide Membranes." *Nanoscale Research Letters* (2015).

Ltd, Metal Finishings. How Will Anodizing Affect The Dimensions of my Part. *https://metalfinishingsltd.co.uk/articles/anodising-dimensions/*. n.d. 2021.

M., Zhang. "Determination of the total mass of antioxidant substances and antioxidant capacity per unit mass in serum using redox titration." *Bioinorganic chemistry and applications* (2014).

Madakson P. B, Malik I. A , Laminu S. K , Bashir I. G. "Effect of Anodization on the corrosion behavior of Aluminium Alloy in HCl acid and NaOH." *International Journal of Materials Engineering* (2012).

Management, Global Safety. "Sodium Hydroxide, 0.5M." Safety Data Sheet. 2014.

—. "Sulfiric Acid, 3M." Safety Data Sheet. 2015.

Praxiar. "Praxair Material Safety Data Sheet; Hyrogen Gas." 07 2007. *http://dept.harpercollege.edu/chemistry/msds/Hydrogen%20Compressed%20Gas%20Praxair.pdf.* 2021.

Tsangaraki-Kaplanoglou, I. "Effect of alloy types on the anodizing process of aluminum." *Elsevier* (2005).

World, Anodizing. Why Sealing Process is so Important. 2009. *https://aluminumsurface.blogspot.com/2009/04/why-sealing-process-is-so-important.html*. n.d. 2021.