

Colourization of anodized Aluminium at different anodization times for improved thermal emittance

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ABSTRACT

The main aim of this study was to produce a surface good enough to emit radiation received from the sun to produce a cooling effect while protecting the surface from conditions such as corrosion by the principles of anodization and colouring. Eight aluminium sample plates were polished and then brightened in a brightening mixture of phosphoric acid, nitric acid, and copper nitrate solution at 80 °C. The brightened aluminium sample plates were anodized in sulphuric acid at 18 – 20 °C for different anodization times of 5 - 50 minutes. The anodized brightened aluminium plates were sealed and coloured by immersion into lead acetate and potassium permanganate solutions respectively at 18 – 20 °C. The thermal emittances of the brightened anodized and coloured anodic films of the sample plates as well as the thickness of the anodic films were determined by the use of an emissometer and gravimetric method respectively. The colouring of the sulphuric acid anodized aluminium plates produced hard coloured anodic films, with interference colours of dark-brown, golden-brown, yellowish-brown, deep brown and golden-yellow on the samples with high emittance values, depending on the anodizing time. The yellowish-brown coloured anodized aluminium plate obtained at anodization time of 40 minutes was found to be the most favourable, with high emittance value of 0.86 ± 0.01 and film thickness value of $0.97 \pm 0.01 \mu\text{m}$. This coloured anodic film produced on the aluminium sample plate could be used as thermal control coating in spacecraft, in some electronic gadgets, and in the production of aluminium cooling roofs to produce a cooling effect during hot weather conditions, and also for protective and decorative purposes.

Keywords: Anodization, colouring, emissometer, emittance and anodized aluminium plate

Introduction

Research has shown that pure aluminum reacts readily with oxygen to form a thin film of aluminum oxide (Al_2O_3) ranging in thickness from 0.01 – 0.04 μ (Hass, 1946). This oxide film forms an impenetrable layer that is firmly bonded to the surface and thus prevents further oxidation of the aluminium. This layer can be lost through wearing off. To prevent wearing, a much thicker film is needed to improve the mechanical properties of aluminium and its alloys by an anodizing process (Wernick *et al.*, 1987; Wernick and Pinner, 1972; Young, 1961).

Anodized aluminium extrusion was a popular architectural material in the 1960s and 1970s, but has since been replaced by cheaper plastics and powder

coating. The films produced after anodizing can be employed for cosmetic effects, either with the thick porous coatings that are capable of absorbing dyes or colours or with thin transparent coating that adds an interference effect to reflect light (Shearsby and Pinner, 2001).

Anodizing, according to Sheasby and Pinner (2001), was first used on an industrial scale in 1923 to protect duralumin seaplane parts from corrosion. The process, which was chromic acid-based, was called the Bengough-Stuart process because it was first reported by Bengough and Stuart in 1924, and this was documented in British defence specification DEF STAN 03-24/3.

Many acids are employed in the anodization process, but sulphuric acid, which was patented by Gower and O'Brien in 1927, has become the most common anodizing electrolyte and the best coating for dyeing or colouring metals such as aluminium and its alloys. One such anodizing acid is oxalic acid. Anodizing started in Japan in 1923 and was later carried out by the Germans. It was first employed for architectural application, but is now being used in many other fields. Phosphoric acid anodizing is what is used as a pretreatment for adhesives or organic paint (Sheasby and Pinner, 2001).

The anodization process is usually carried out in an electrolytic bath containing an electrolyte such as aqueous sulphuric acid, with a lead or carbon plate as the cathode and the aluminium or its alloy to be anodized attached to the anode on which a thick aluminium oxide film is formed when direct current flows. The anodizing treatment conditions and the composition of a single acid electrolyte (chromic acid, phosphoric acid, oxalic acid, sulfuric acid, etc.) have been used to optimize the properties of the anodic layer (Mezlini, 2006; Lunder, 2005; Jagminas, 2001; Lopez, 2000). The anodic films are porous and have a close-packed columnar structure that is oriented at a right angle to the barrier layer (Greenblatt, 1962; Keller *et al.*, 1953).

The anodization of aluminium is thus the production of anodic oxide films on aluminium or its alloy. It has become well known today and is being employed in many electronic sectors as well as for space applications and in the roofing of buildings. Anodizing serves as the best solution in protecting surfaces of metals and their alloys by increasing the thickness of their oxide layer surfaces. Examples of such metals are steel, magnesium, zinc, titanium, niobium, aluminum and their alloys. However, the anodization of aluminum is well employed for so many applications due to its unique characteristics such as its low density which accounts for its light weight; its excellent conduction of heat and electricity; and its qualities as a good reflector of both visible and radiated heat.

The anodized aluminium surfaces tend to be harder and thicker than those of unanodized aluminium, but tends

to have a low ability to moderate wear resistance after a period of time, hence the need for sealing and colouring to help increase the thickness (since anodizing does not increase the strength of the metal) so as to be able to enhance corrosion resistance.

The films can be readily sealed to close the pores at the surface, and then coloured by inorganic solutions and organic dyes, electrolytic and integral colouring anodizing processes; however, the thickness of the porous film layer is dependent on the current density and anodizing time (Wood and O'Sullivan, 1969; O'Sullivan *et al.*, 1968; Spooner and Forsyth, 1968). The colouration process of the films produced was first studied by Kape and Mills (1974).

Colouring of aluminium as well as metals such as stainless steel could be the best method for reducing corrosion, most especially on solar collectors. Types of colouring include black permanganate conversion coating, inorganic colouring, integral black colouring and electrolytic black colouring (Umarani *et al.*, 2011, 2002; Sharma *et al.*, 1997).

The anodizing and colouring processes can also be used for producing decorative and protective films on products made from aluminium and its alloys (Akhabue and Ilenikhena, 2013; Sharma and Sharma, 1983; Wernick and Pinner, 1972), and passive thermal control coatings (Sharma *et al.*, 1997; Sharma and Sridhara, 2012). The processes are more economical when these coloured anodic oxide films' thermal emittances are found so as to be used for the right purposes.

A low thermal emittance anodized aluminum could be employed in places or gadgets that need heat in their applications, whilst a high thermal emittance coloured anodized aluminium could be employed in areas where there is the need to reduce heat, since thermal heat is radiated back into the atmosphere much faster when the thermal emittance is high than when it is low.

Stefan-Boltzmann law is applied to compare emission rates from different surfaces.

The Stefan-Boltzmann law is:

$$P = \epsilon \sigma AT^4 \quad 1$$

P - power radiated (Watts)

ϵ - emissivity (no units)

σ - Stefan-Boltzmann constant = $5.67 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4}$

T - temperature (K)

This formula calculates the amount of power radiated by an object; hence it is used in finding emissivity by using ratios. This is shown in equation (2)

Emissivity is a dimensionless quantity defined as the power radiated by a surface divided by the power radiated from a black body of the same surface area and temperature. In simpler terms, it is the relative ability of a surface to emit energy by radiation. A true black body has an emissivity of 1.

$$\epsilon = \frac{P_s(T)}{P_{bb}(T)} \quad 2$$

$P_s(T)$ - power radiated by unknown sample at temperature T

$P_{bb}(T)$ - power radiated by perfect blackbody at the same temperature T

One can use a standard known sample as reference in order to compare values. The relation then becomes

$$\frac{P_s(T)}{P_r(T)} = \frac{\epsilon_s \sigma AT^4}{\epsilon_r \sigma AT^4} = \frac{\epsilon_s}{\epsilon_r} \quad 3$$

(if sample and reference have the same surface area and are at the same temperature T)

$P_r(T)$ - power radiated by reference sample at the same temperature T

ϵ_r - emissivity of reference material.

ϵ_s - emissivity of unknown material.

The emissometer is calibrated to measure voltage, so the power emitted is proportional to the voltage measured by the instrument, where

$$\frac{\epsilon_s}{\epsilon_r} = \frac{V_s}{V_r} \quad 4$$

$$\epsilon_s = \frac{V_s}{V_r} \times \epsilon_r \quad 5$$

V_s - voltage measured using the sample

V_r - voltage measured with the known reference material.

This research aims at producing coloured sulfuric acid anodized aluminium oxide films on sample plates at different anodizing times with high thermal emittance to be employed at high temperature regions since a cooling effect is needed in these regions. There is therefore the need for more gadgets to be made using colored anodized aluminium with high thermal emittance. This helps protect the interior and exterior of most metallic surfaces in order to be used over a long period of time.

The experiment

Preparation and brightening of Aluminium Sample Plates

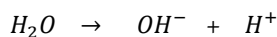
Sample plates of 7cm by 7cm were polished with two main types of abrasives (P100 and P800; 162 and 25.8 μm) of increasing grit corresponding to decreasing grain particles until the plates had an even mirror finish. The plates were then washed in a detergent solution, thoroughly rinsed in distilled water and dried. They were then brightened in a heated brightened mixture made of four molar concentrations each of concentrated Nitric acid [HNO_3], Phosphoric acid [H_3PO_4] and Copper (II) Nitrate Trihydrate [$\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$] in a 300ml beaker.

Anodization Process

The anodization process was carried out in an electrolytic bath using a 5 molar sulfuric acid as the electrolyte, lead plate as the cathode and a brightened aluminium plate as the anode. The anodization times were varied from 20 to 50 minutes in steps of 5 minutes for each plate. The anodized plates were rinsed in distilled water and drip dried. The ionic equations of the anode reactions are



i

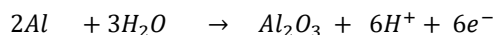


ii



iii

The overall equation for the anodization is

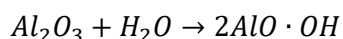


iv

where Al is the aluminium and Al_2O_3 is the aluminium oxide layer.

for over 15 minutes helps to increase the resistance of the anodized aluminium against chemical corrosion agents such as H^{+} and Cl^{-} .

During the period of immersion, whitish fumes were seen to have been released from the pores due to water reacting with aluminium oxide to produce the mineral Boehmite – $Al_2O_3 \cdot H_2O$ or $AlO \cdot OH$. The equation for the formation of Boehmite, a hard, transparent material that has a greater volume than the aluminium oxide formed, is



Sealing Process

The sealing process was used to close off the pores at the surface of the oxide layer. This was done by immersing each of the anodized aluminum plates in a 0.4 molar lead acetate solution at 18 to 20 °C for 15 minutes. The sealing

Colouring of Anodized Plates

The sealed anodized aluminium plates were placed in a 0.4 molar potassium permanganate solution at 18 - 20°C for 10 minutes until a deep yellow-brown / brown colour was formed on the aluminium oxide layer.

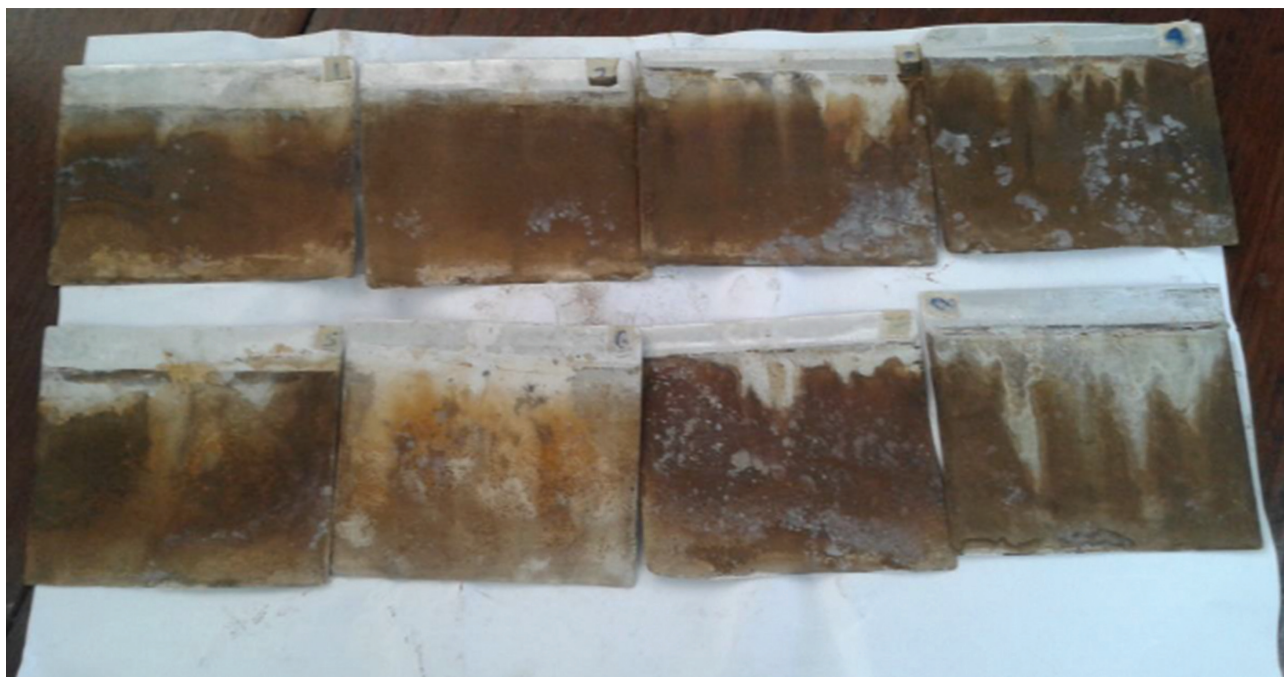


Fig.1: Colour of plates after sealing and colouring

Measurement of thermal emittance and thickness of the film produced

The thermal emittance of the sample plates was measured using an emissometer with an output that was linear, and had emissivity and a near-constant response to infra-red wavelengths of 3 – 30 μm . The detector of the instrument was heated to 341°K (68°C) so that the samples did not have to be heated, and it was calibrated from time to time with a standard black and polished aluminum standard plate. The thickness of the film for each anodized and coloured anodized sample plate was calculated using the gravimetric method of measurement.

Results and discussion

Coloured anodic films with high thermal emittance values were successfully produced on brightened aluminium sample plates by anodizing in an electrolytic bath of 5 molar concentration sulphuric acid as electrolyte at 18 – 20°C for different anodizing times of 20 to 50 minutes. The anodic films were sealed in 0.4 molar lead acetate solution and coloured in 0.4 molar potassium permanganate solution at 18 – 20°C for 15 and 10 minutes respectively. The emittance values and patterns are presented in tables 1-9 and figures 2-5.

Table 1 shows that the thermal emittance of brightened aluminium sample plates had an average value of $\epsilon = 0.68 \pm 0.01$. This value compares well with values of a brightened aluminium sample plate of $0.64\text{--}0.72 \pm 0.01$ (Akabue and Ilenikhena, 2013). The difference in emittance values was due to the purity and surface treatment conditions of the aluminium used.

Table 2 and Figure 2 show the increase in thermal emittance with increasing anodization time from 0.84 to 0.90 ± 0.01 . It could be seen that the plate used at the 45th minute had a decrease in thermal emittance with a value of 0.869, but the plate brightened at the 50th minute had an increase in thermal emittance value of 0.901 after the anodization process. This could be due to the plate not being well rinsed in distilled water after the brightening process, hence making room for the drop in thermal emittance and subsequently the thickness after the anodization process.

Tables 3 and 5 show the changes in thermal emittance of the brightened sample plates after anodization with increasing anodization time.

The thermal emittance values of the coloured anodized aluminium plates presented in Table 4 and Figure 3 were found to be high and varied from 0.63 to 0.86 ± 0.01 with increasing anodization times, though with a small drop after the 40th minute due to the effect from the anodization process. These emittance values still compared well with thermal emittance values of $0.74\text{--}0.81 \pm 0.01$ (Akabue and Ilenikhena, 2013) for coloured anodized aluminum plates. They also compared favorably with emittance values of $0.72\text{--}0.90$ for inorganic black coloured anodized aluminium alloys (Sharma *et al*, 1997) {110, 2024 and 6061}), the emittance value of 0.834 for the exterior part of anodized aluminum surfaces (Gustavsen and Berdahl, 2003) and 0.9 for treated (anodized or painted) exterior and interior parts of cavities of aluminum surfaces (Mitchel *et al*, 2000).

The result of the thermal emittance values obtained for coloured anodic films showed a small decrease compared to the thermal emittance values before the colouring process. This reduction could be attributed to the hardening of the porous anodized film by the sealing process before colouring and the fact that the sealing was not done in a steam bath.

Tables 6 and 7 provide the mass values for the Aluminum plates before and after the anodization respectively. From these values, the mass of the thin films were measured and used to obtain the thickness of the film. Table 8 and figure 4 show that thermal emittance values increase with increasing thickness of anodized films on aluminium sample plates. The thickness of the coloured films varied from $0.032\text{--}3.157 \pm 0.001\ \mu\text{m}$ with anodization time from Table 9 and Figure 5. These values are low when compared to $7.0\text{--}36.0\ \mu\text{m}$ for inorganic black coloured anodized aluminium alloys (Sharma *et al*, 1997 {110, 2024 and 6061}), but compared well with $1.808\text{--}7.446 \pm 0.001\ \mu\text{m}$ for coloured anodized aluminum plates (Akabue and Ilenikhena, 2013).

Table 1: Thermal emittance of brightened polished aluminium sample plates

Plate number	Masses of plate		voltmeter reading		Thermal emittance of the brightened plate
	UnBrightened plate m	Brightened plate m	Blackbody plate	Brightened plate	
1	10.980	10.607	3.03	2.03	0.623
2	9.355	9.068	3.03	2.08	0.638
3	12.432	12.164	3.03	2.23	0.684
4	12.241	11.883	3.03	2.29	0.703
5	11.816	11.404	3.03	2.30	0.706
6	13.616	13.356	3.03	2.30	0.706
7	11.192	10.890	3.03	2.32	0.712

Table 2: Thermal emittance of anodized aluminium sample plates

Plate number	voltmeter reading		Thermal emittance of the anodized plate	Anodization time (minutes) T(mins)
	Blackbody plate	Anodized plate		
1	3.05	2.76	0.842	20.0
2	3.05	2.80	0.854	25.0
3	3.05	2.83	0.863	30.0
4	3.05	2.85	0.881	35.0
5	3.05	2.89	0.881	40.0
6	3.05	2.89	0.869	45.0
7	3.05	2.96	0.903	50.0

Table 3: Change in thermal emittance of brightened aluminium plates after anodizing

Plate number	Thermal Emittance			Anodization time(minutes) Tmins
	Brightened polished aluminium plate ϵ	Anodized polished aluminium plate ϵ	Change in thermal emittance ϵ	
1	0.623	0.842	0.219	20.0
2	0.638	0.854	0.216	25.0
3	0.684	0.863	0.179	30.0
4	0.706	0.881	0.175	35.0
5	0.706	0.881	0.175	40.0
6	0.703	0.869	0.166	45.0
7	0.712	0.903	0.191	50.0

Table 4: Thermal emittance of coloured anodized aluminium sample plate

Plate number	voltmeter reading		Thermal emittance of the coloured anodized plate	Anodization time(minutes) tmins	Surface Film colour
	Blackbody plate	Coloured anodized plate			
1	2.99	2.01	0.625	20.0	Dark-brown
2	2.99	2.35	0.731	25.0	Dark-brown
3	2.99	2.57	0.799	30.0	Golden-brown
4	2.99	2.71	0.843	35.0	Golden-brown
5	2.99	2.76	0.858	40.0	Yellowish-brown
6	2.99	2.09	0.650	45.0	Golden-yellow
7	2.99	2.42	0.753	50.0	Deep-Brown

Table 5: Change in thermal emittance of brightened aluminium sample plates after colouring of anodic films

Plate number	Thermal Emittance			Anodization time(minutes) Tmins
	Brightened aluminum plate ϵ	Coloured anodized plate ϵ	Change in thermal emittance ϵ	
1	0.623	0.625	0.002	20.0
2	0.638	0.731	0.093	25.0
3	0.684	0.799	0.115	30.0
4	0.706	0.843	0.137	35.0
5	0.706	0.858	0.152	40.0
6	0.703	0.650	0.053	45.0
7	0.712	0.753	0.041	50.0

Table 6: Mass of film of anodized sample plates

Plate No	Mass of Brightened sample plate $m_1 \pm 0.001$ (g)	Mass of anodized plate $m_2 \pm 0.001$ (g)	Mass of anodic film $m \pm 0.001$ (g)	Anodization time(minutes) Tmins
1	10.607	10.623	0.016	20.0
2	9.068	9.143	0.075	25.0
3	12.164	12.288	0.124	30.0
4	11.883	12.008	0.125	35.0
5	11.404	11.778	0.374	40.0
6	13.356	13.731	0.375	45.0
7	10.890	11.308	0.418	50.0

Table 7: Mass of film of coloured anodized sample plates

Plate No	Mass of brightened sample plate $m_1 \pm 0.001$ (g)	Mass of coloured anodized plates $m_2 \pm 0.001$ (g)	Change in mass $m \pm 0.001$ (g)	Anodization time(minutes) Tmins
1	10.607	10.608	0.001	20.0
2	9.068	9.078	0.010	25.0
3	12.164	12.176	0.012	30.0
4	11.883	11.905	0.022	35.0
5	11.404	11.433	0.029	40.0
6	13.356	13.263	0.093	45.0
7	10.890	10.794	0.096	50.0

Table 8: Thickness of anodized films on aluminum plates

Plate No	Mass of film $m \pm 0.001$ (g)	Height of film $h \pm 0.01$ (cm)	Width of film $w \pm 0.01$ (cm)	Area of film $A \pm 0.001$ (cm ²)	Thickness of film $t \pm 0.001$ (μ m)	Emissivity of the anodized plate	Anodization time(minutes) Tmins
1	0.016	5.50	7.60	41.800	0.485	0.842	20.0
2	0.075	6.20	7.20	44.640	2.127	0.854	25.0
3	0.124	6.20	7.50	46.500	3.376	0.863	30.0
4	0.125	6.20	7.40	45.880	3.449	0.869	35.0
5	0.374	6.30	7.30	45.990	10.294	0.881	40.0
6	0.375	6.20	7.30	45.260	10.488	0.881	45.0
7	0.418	6.20	7.40	45.880	11.533	0.903	50.0

Table 9: Thickness of coloured anodized films on aluminum plates

Plate No	Mass of film $m \pm 0.001$ (g)	Height of film $h \pm 0.01$ (cm)	Width of film $w \pm 0.01$ (cm)	Area of film $A \pm 0.001$ (cm ²)	Thickness of film $t \pm 0.001$ (μ m)	Emissivity of the coloured anodized plate	Anodization time(minutes) Tmins
1	0.001	6.40	7.50	48.000	0.032	0.625	20.0
2	0.010	6.10	7.20	43.920	0.345	0.731	25.0
3	0.012	6.40	7.50	48.000	0.379	0.799	30.0
4	0.022	6.10	7.30	44.530	0.749	0.843	35.0
5	0.029	6.20	7.30	45.260	0.971	0.858	40.0
6	0.093	6.20	7.20	44.640	3.157	0.650	45.0
7	0.096	6.40	7.20	46.080	3.157	0.753	50.0

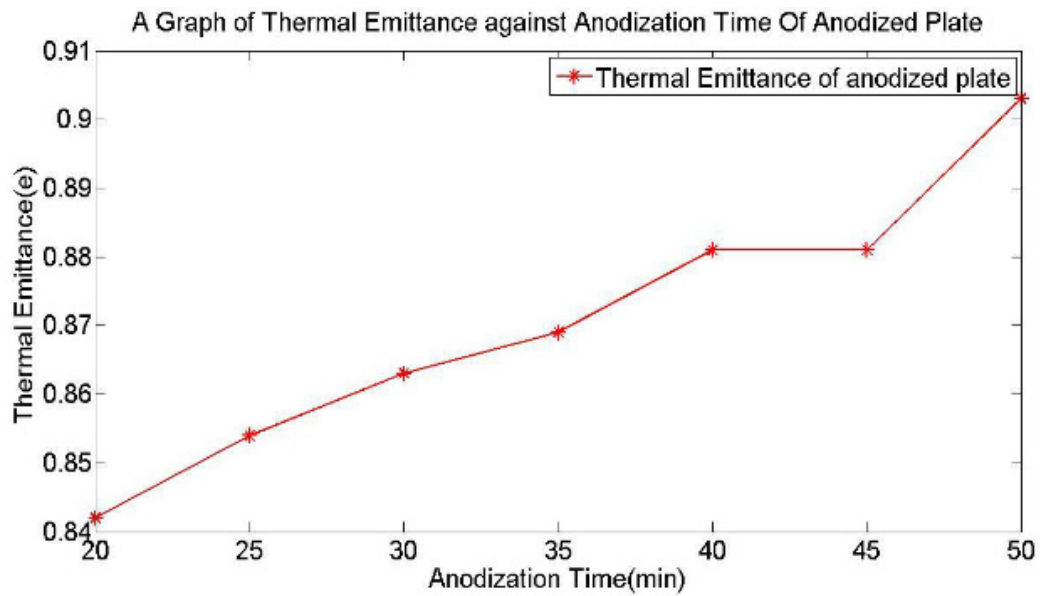


Fig. 2: A Graph of Thermal Emittance against Anodization Time of Anodized Plate

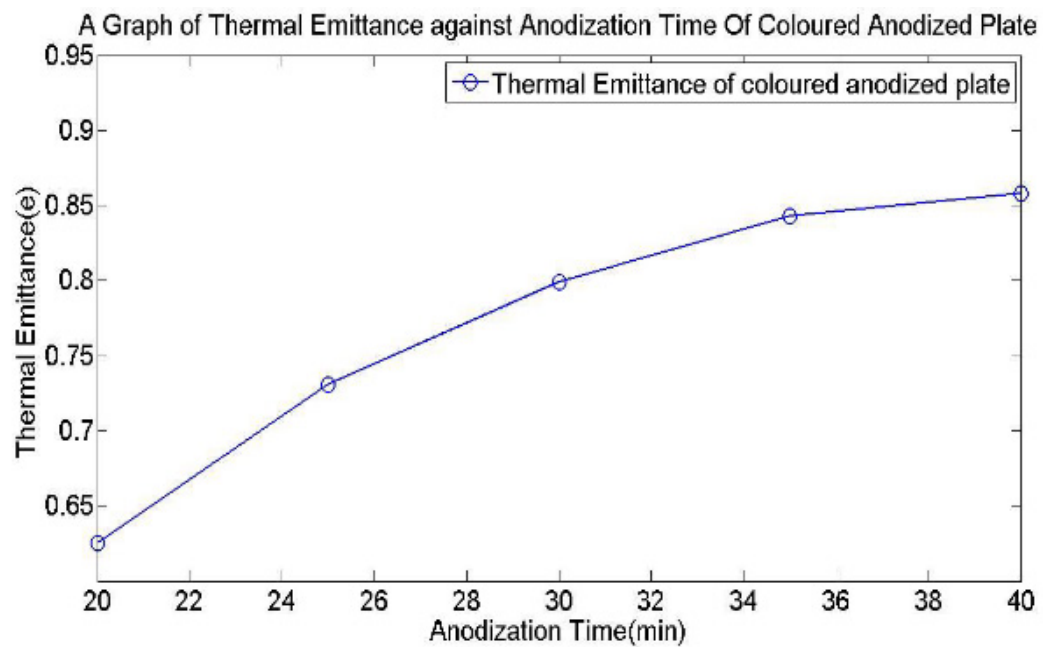


Fig. 3: A Graph of Thermal Emittance against Anodization Time of Coloured Anodized Plate

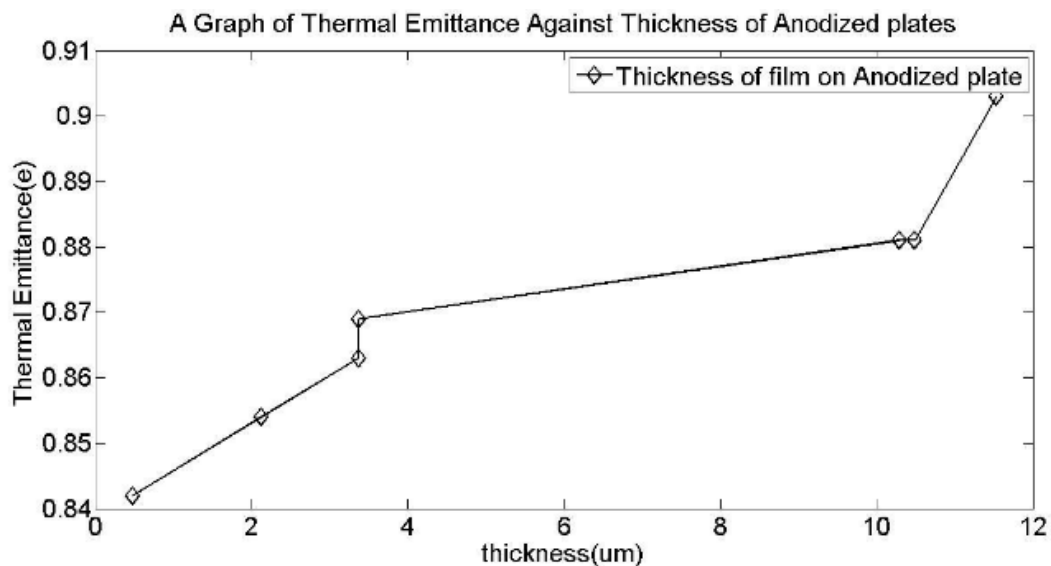


Fig. 4: A Graph of Thermal Emittance against Thickness of Anodized Plates

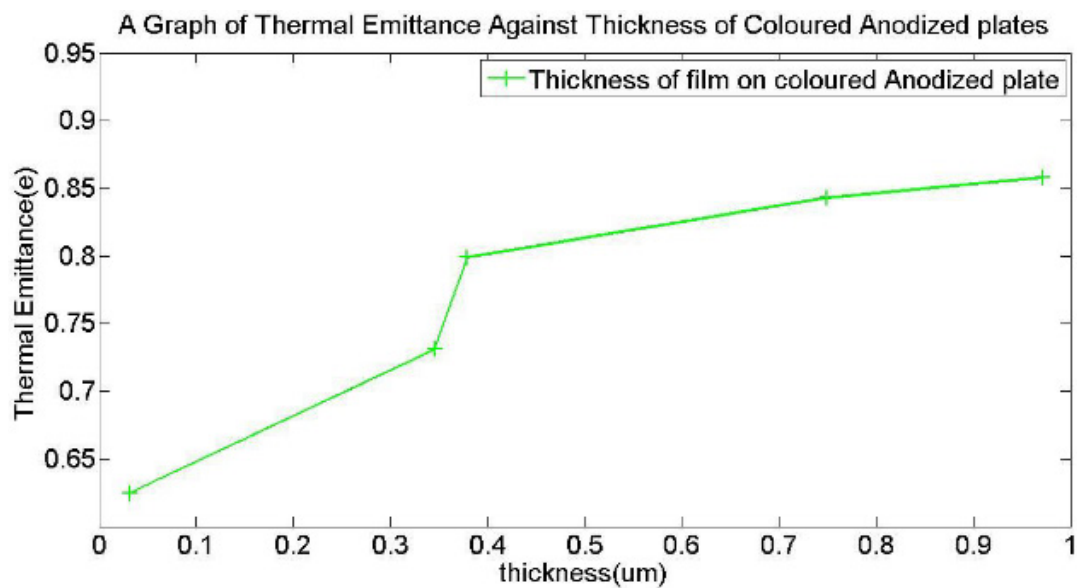


Fig. 5: A Graph of Thermal Emittance Against Thickness of Coloured Anodized Plates

The low values of thickness for the coloured anodized aluminum films could be attributed to deposition conditions and treatments of anodized aluminum films during sealing and colouration processes using the lead acetate and potassium permanganate solutions respectively. The colouring of the anodic films produced

different surface film colours on the sample plates as shown in Fig. 1, among which were dark-yellow, golden-brown, yellowish-brown, deep yellowish-brown and brown with increasing anodization times respectively.

Conclusion

Coloured anodic films with high thermal emittance were successfully produced on brightened aluminium sample plates by an anodizing process using a 5 molar sulphuric acid for different anodization times of 20-50 minutes followed by sealing and colouration of the anodized films. Solutions were controlled with regard to concentration and time. The sample plate was thoroughly rinsed after each stage to ensure that it entered the next process in the correct state. This was done to prevent irregularities in the results and minimize the contamination of solutions from one stage by the preceding stage. The coloured anodic films have interference colours of dark-brown, golden-brown, yellowish-brown, golden-yellow and deep-brown on the samples, depending on the anodizing time. The yellowish-brown coloured anodized aluminium plate obtained at anodization time of 40 minutes has the most favourable high thermal emittance value of 0.86 ± 0.01 and film thickness value of $0.97 \pm 0.01 \mu\text{m}$. This anodized aluminium plate is suitable for application as thermal control coating to give a conducive temperature in spacecraft, electronic industries and in the production of aluminum roofing sheets for houses to limit radiant heat transfer.

References

- Akhabue, E. O. and Ilenikhena, P.A. (2013). Effect of deposition time on thermal emittance of bright chrome plated stainless steel for photothermal solar energy conversion, *Nigeria Journal of solar energy*, 24: 76-79.
- Akhabue, E. O. and Ilenikhena, P.A. (2013). Colouration of anodized aluminium plates and its thermal emittance properties, *Nigeria Journal of Solar Energy*, 24: 64 – 67.
- Defence Standard. 1997. Chromic acid anodizing of aluminium and aluminium alloys. DEFSTAN 03-24:Issue 3, 5 September, 1997.
- Greenblatt, G. H. (1962). Structure of oxide films form on aluminium after exposure to high – temperature pure water, *Journal of Electrochemical Society* 109 (12): 1139 – 1142.
- Hass, G. (1946). Silicon monoxide protected front surface mirrors, *Optics*, 1:134.
- Jagminas, A., Bebeliene, D., Mikulska, I., Tomasiunas, R. (2001). Growth peculiarities of aluminium anodic oxide at high voltages in diluted phosphoric acid, *Journal of Crystal Growth*, 233: 591.
- Kappe, J. M. and Mills, E. C. (1974). Long-term outdoor exposure of anodic coatings coloured by precipitation of inorganic pigments, *Transactions of Institute of Metal Finishing*, 14: 407.
- Mezlini, S., Elleuch, K., Fouvry, S., Kapsa, Ph. (2006). The effect of sulphuric anodization of aluminium alloys on contact problems, *Surface coating technology journal*, 200: 2852.
- O’Sullivan, J. P., Hockey, J. A. and Wood, G. C. (1968). Infrared spectroscopic study of anodic alumina films, *Transactions of the Faraday Society*, 65 :336 – 340.
- Sharma, A. K., Bhojraj, H., Kaila, V. K. and Narayanamurthy, H. (1997). Anodizing and inorganic black colouring of aluminium for space applications, *Transactions of Institute of Metal Finishing*, 95 (2): 14 – 20.
- Sharma, A. K., Bhojraj, H., Kaila, V. K. and Narayanamurthy, H. (1997). Anodizing and inorganic black colouring of aluminium for space applications, *Transactions of Institute of Metal Finishing*, 95 (2): 14 – 20.
- Sharma, A. K. and Sridhara, N. (2012). Degradation of thermal control materials under simulated radiative space environment, *Advances in space Research*, 50(10):1411-1424.
- Sheasby, P. G.; Pinner, R. (2001). The Surface Treatment and Finishing of Aluminium and its Alloys (sixth ed.). Materials Park, Ohio & Stevenage, UK: ASM International & Finishing Publications.
- Umarani, R. and Sharma, A. K. (2002). Studies of black molybdate conversion coating in aluminium alloys, *Galvanotechnik*, 93 (7): 1736 – 1746.

- Umarani, R., Subba, Y. and Sharma, A. K. (2011). Studies on black anodic coatings for spacecraft thermal control applications, *Galvanotechnik*, 102:2182.
- Wernick, S. and Pinner, R. (1972). Surface treatment and finishing of aluminium and its alloy, 4th edition, Robert Draper Ltd., Teddington, UK.
- Wernick, S, Pinner, R., Sheasby, P. (1987). Surface treatment of aluminium and its alloys, 5th edition Finishing Publication Ltd., UK.
- Wood, G. C. and O'Sullivan, J. P. (1969). Electron optical examination of sealed anodic alumina films, surface and interior effects, *Journal of the Electrochemical Society*, 116(10): 1351 – 1357.