

Controlled Texturing of Aluminum Sheet for Solar Energy Applications

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Abstract

Aluminum sheets were polished to reduce ruggedness and then textured in varying acid-ethanol concentration etchant to form pores. The textured surface was characterized structurally by using X-ray diffraction (XRD) which revealed aluminum crystallographic planes (1 1 1), (2 0 0), (2 2 0) and (3 1 1). Its morphology was studied by using energy dispersive X-ray (EDX) and scanning electron microscope (SEM) that confirmed purity of aluminum sheet to be 99.66% at. Reflectance of textured and plain aluminum sheet was analyzed by spectrophotometric measurements which showed that texturing reduced the reflectance of the polished surface by 26% in the UV-VIS-NIR spectrum of solar radiation. With reduced reflectance of the textured aluminum sheet, it was applicable for solar radiation absorption.

Keywords

Aluminum, Texturing, Reflectance, Solar Energy, Electro-Polishing

1. Introduction

High energy demand to support sustainable development has prompted research into alternative energy sources to compliment the conventional sources [1]. Out of these alternative sources, solar energy can be harnessed directly using simple stand-alone systems, and furthermore it is environmentally friendly and a renewable energy source [2]. The challenge to harness solar energy has been the efficiency at which it is harnessed and hence the need to engineer properties of materials [3]. In solar thermal systems, selective absorber surfaces may also be realized through creating a texture of a suitable scale deposited on a highly reflecting metal substrate. The tex-

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textured surface absorbs solar radiation by trapping the light through geometric effects of multiple reflection and absorption as one of the ways by which photon management can be enhanced [4]. Texturing requires that the surface of the substrate is made smooth if some orderings of the texturing features are to be achieved. This smoothing is in other term called polishing achievable by electrolysis and by chemical process [5]. Textured surfaces have found applications in fields like photovoltaic and manufacture of electronic devices such as super capacitors [6]. In this study, aluminum sheet is polished and textured to improve its optical properties for use as substrate in flat plate solar thermal collector to harness thermal energy. Electro-polishing of aluminum substrates is accomplished by making the substrates the anode in an electrolytic cell.

2. Experimental Procedures

2.1. Substrate Preparation and Cleaning

Commercially obtained aluminum sheets from Kenya Industrial Area, Kenmetals Ltd. (Nairobi-Kenya) with a data sheet showing 99.9% purity of 0.5 mm thick were cut into pieces of 4.0 cm × 1.5 cm. The pieces were cleaned in an ultrasonic bath of acetone for 5 minutes to degrease them. Degreased pieces were rinsed in distilled water to remove traces of acetone and left to dry in air.

2.2. Preparation of Polishing Electrolyte

Commercially obtained 70% pure undiluted perchloric acid (HClO_4) from RFCL Limited, India was added in small quantities to ethanol in a beaker. The reaction between ethanol and perchloric acid is exothermic. Therefore, ethanol in the beaker was kept at a temperature below 10°C as perchloric acid was added. The ratio of perchloric acid to ethanol was 1:4 by volume.

Heat is generated as current passes through the electrolyte, and ethanol moderates the viscosity of the electrolyte and acts as a solvent for the molecules and ions. Perchloric acid ensures that required low pH favorable for the formation of Al^{3+} ions is maintained, and does not react to form other ions at the anode and also cools the electrolyte [7].

2.3. Electro-Polishing of the Substrate

Figure 1 shows the electrolytic cell used to electro polish the substrate. Graphite electrode was used for the cathode while the cleaned aluminum piece was made the anode. Voltage was applied gradually to the electrodes

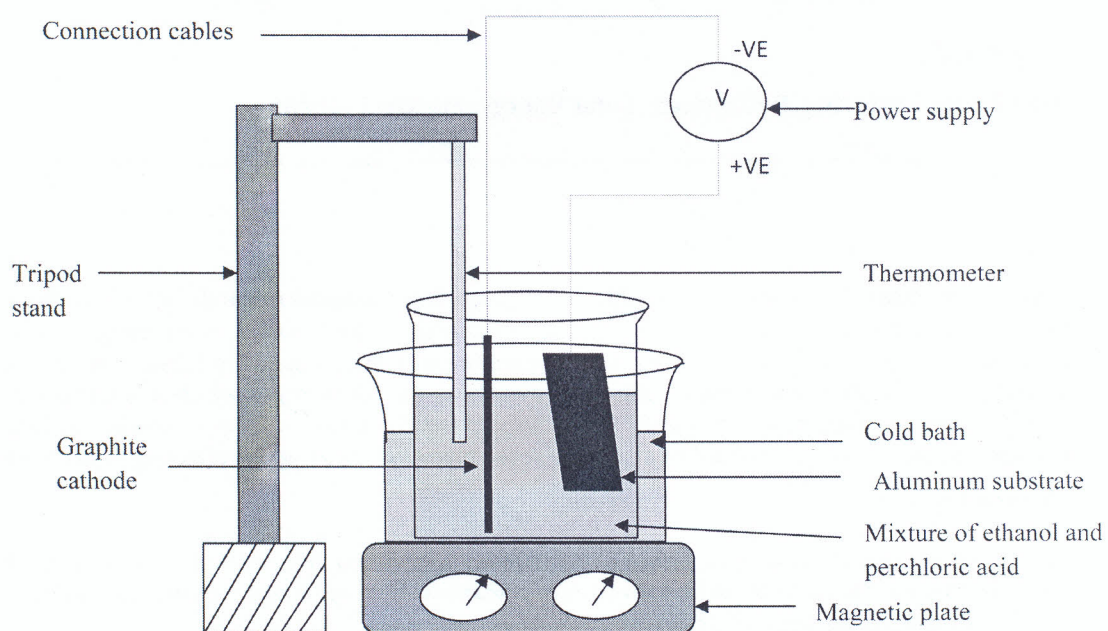


Figure 1. Set up for electro-polishing process.

that were immersed in the electrolyte hence the current drawn by electrolyte also varied. Since current generates heat, to ensure even temperature in the electrolytic solution continuous stirring using a magnetic stirrer was used. The temperature of the electrolytic solution was monitored using a mercury thermometer and kept below 25°C. The low temperatures were observed to prevent rapid oxidation by perchloric acid that occurs at temperatures above 38°C. During the electro-polishing the applied voltage and the current drawn were recorded stepwise. The temperature kept rising from 0°C to 25°C. The sample was removed and rinsed in de-ionized water to wash off remnants of the electrolytic solution.

2.4. Texturing

A solution of 1.0 M of perchloric acid from RFCL Limited, India was mixed with ethanol in the ratio of 1:2 by volume. The mixture was cooled and maintained at temperatures below 10°C by immersing the beaker with the mixture in an ice bath whose temperature was continuously monitored. Using graphite electrode as the cathode and polished aluminum as the anode a dc voltage of 30 V was supplied for 15 minutes. Figure 2 shows the set up for the texturing process.

3. Results and Discussion

3.1. Current-Voltage Characteristics during Electro-Polishing

Typical current density-applied voltage curves have been reported earlier by [8] that sets standards and safety guidelines for electro-polishing where electrolytes are basically classified in two categories; 1) perchloric acid in alcoholic electrolyte and 2) mineral acid in organic solution electrolyte. The typical current density-applied voltage curve for perchloric acid in alcoholic electrolyte takes the form in Figure 3 and electro polishing occurs

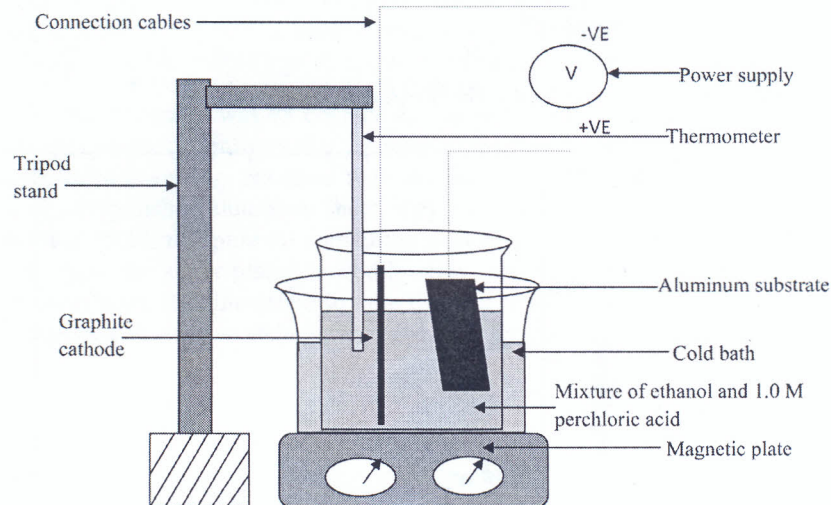


Figure 2. Set up for texturing process.

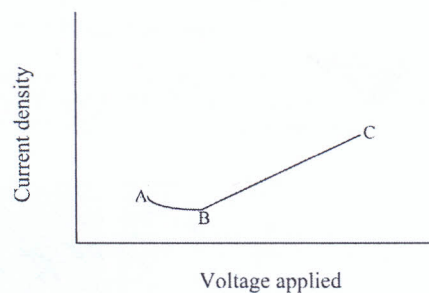


Figure 3. Characteristic electro polishing current density-applied voltage curve for perchloric acid in alcoholic electrolyte [8].

between B and C region [8].

Figure 4 shows measure current-voltage characteristics during electro-polishing of aluminum samples. Ideally Figure 4 should mimic Figure 3, but it was noticed that the point where the gray colour of the sample begins to peel off was between 10 to 13 volts which indicated the onset of polishing. In Figure 4, it is observed that between 8 to 19 volts there is linear increase of current density with applied potential which is the trend for an ideal electro-polishing curve and this is the region where the samples were electro-polished.

3.2. The Effect of Electro-Polishing on Aluminum Surface Smoothness

The physical observation showed that, after electro polishing, the surface gained luster that resembled metallic mirror. The surfaces of the as cut aluminum piece was rough as shown in magnified picture taken using light microscope (Olympus BX81) at magnification of X50 as shown in Figure 5. After electro polishing, the surface looks smooth and does not show ruggedness as observed in as cut plate under same magnification (Figure 5(b)).

Ruggedness of the surface of as cut aluminum sheet before polishing is unfavorable for effective controlled texturing. The surfaces of the samples were also analyzed using Carl Zeiss SIGMA FE-SEM OXFORD X-ACT scanning electron microscope (SEM) equipped with EDS Detector. The micrographs shown in Figure 6 depict considerable change in surface smoothness whereby ridges and cracks of above 2 μm on the unpolished surface (Figure 6(b)) are considerably smoothed out on polishing (Figure 6(b)). However, sparsely distributed pores of less than 1 μm can be observed on the electro-polished surface.

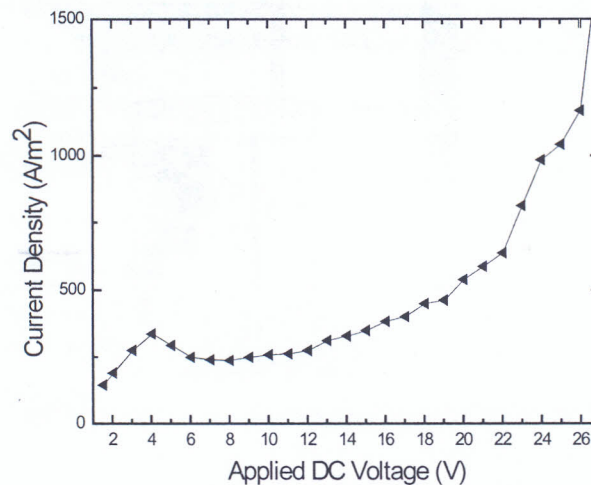


Figure 4. Electro-polishing current density-voltage curve for perchloric acid in alcoholic electrolyte for aluminum sample area 0.0008 m^2 .

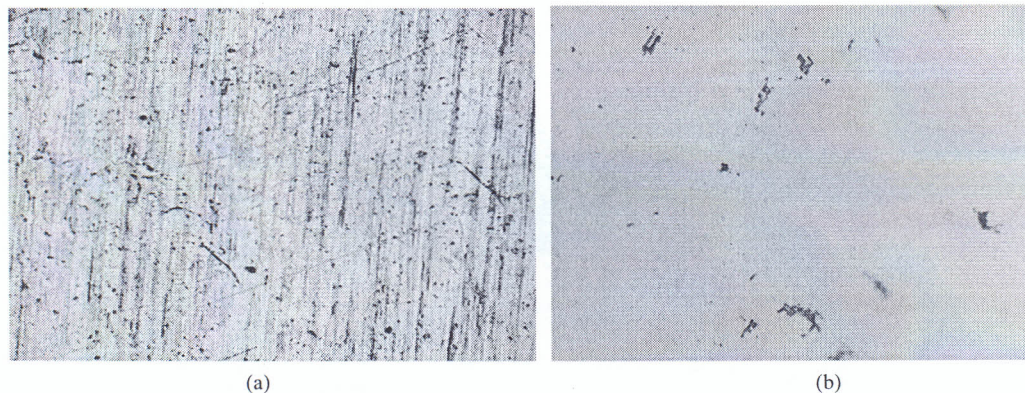


Figure 5. Optical micrograph at $\times 50$ magnification of (a) unpolished as acquired aluminum surface; (b) polished aluminum surface.

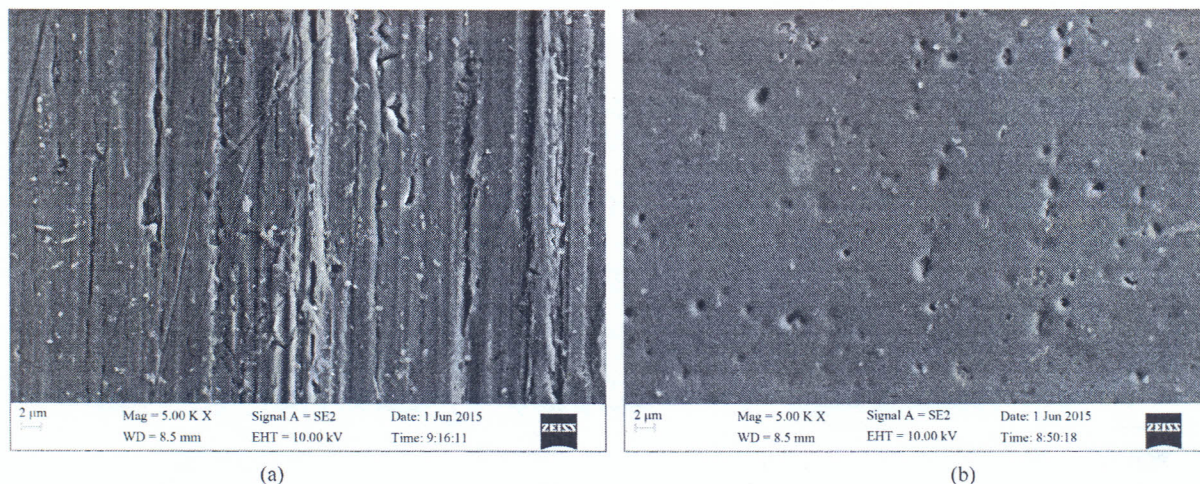


Figure 6. SEM micrograph at $\times 5000$ magnification showing effect of electro-polishing of aluminum sheet on surface smoothness (a) as acquired; (b) electro-polished.

Since the aluminum sheet was commercially obtained, analysis of as-cut samples was carried out using X-ray diffraction (XRD-Phillips, PW 3710 XRD machine) to confirm if the samples were pure aluminum sheet. The results of the analysis are shown in Figure 7. Figure 7(a) shows reference XRD spectrum for aluminum powder (99.99%) obtained from Gaithersburg, Maryland, USA while Figure 7(b) is the pattern obtained for the test aluminum sheets under study.

Figure 7 clearly shows that the peaks obtained for the aluminum substrates resemble very closely those of the reference sample. The intensities seem to differ but the crystallographic planes are similar with prominent peaks appearing at 38, 44, 65 and 78 degrees which corresponds to the (1 1 1), (2 0 0), (2 2 0) and (3 1 1) planes. These are consistent with observation by [9] for aluminum powder (99.99% purity) diffraction. The maximum 2θ angle scan done for the substrates was 95 degrees as opposed to the reference 2θ angle scan which was 140 degrees. This resemblance of peaks confirms that the samples used are indeed aluminum sheets.

In addition, during electro polishing, chemical reaction like oxidation could have taken place. In order to ascertain purity of the electro polished aluminum sheet, they were analyzed using EDX. The EDX analysis in Table 1 depicts the sheet as 99.66 at% pure Al containing 0.34 at% silver impurities. The silver impurities could have been contributed from the silver plated crocodile clips used to hold the samples during electrolysis. The sheet is largely pure aluminum. It is important to note that the absence of oxygen. The commonly formed aluminum oxide, from exposure to air was etched away and even after annealing at 400°C in air the oxide was not formed.

3.3. Texturing

Electro-texturing of the polished aluminum surface was done at different etchant concentrations with an aim of achieving different pore sizes. The concentration was changed by diluting fixed volume of perchloric acid with varying volume of ethanol. Four samples were textured, one in undiluted perchloric and the other three in ethanol diluted perchloric acid at volume ratios of 1:1, 1:2 and 1:3 of acid to ethanol. The SEM micrographs in Figure 8 show the resultant pores for the indicated concentrations.

The aluminum sheet etched in undiluted perchloric acid formed highly populated bigger pores of more than $20\ \mu\text{m}$ wide for a fixed area of view. The sheets etched in diluted etchant concentration have fairly less density of pores of more than $20\ \mu\text{m}$ width and had more pores of less than $2\ \mu\text{m}$ size. This means that undiluted perchloric acid produces a rougher surface compared to the diluted perchloric acid as an etchant. For perchloric acid to ethanol ratios by volume of 1:1, 1:2, 1:3, there is no significant variation in pore population and sizes except that it took longer time to etch the aluminum surface as the acid concentration reduced.

The pores produced by electro-etching aluminum surface in perchloric acid are not uniform in size and do not form repeatable pattern but varies from nanometers range to tens of micrometers. Within the large micrometer sized pores other smaller pores of nanometre and micrometre ranges are co-hosted. This means that electro etching the aluminum sheet in perchloric acid forms pores within pores shown in a SEM micrograph in Figure 9.

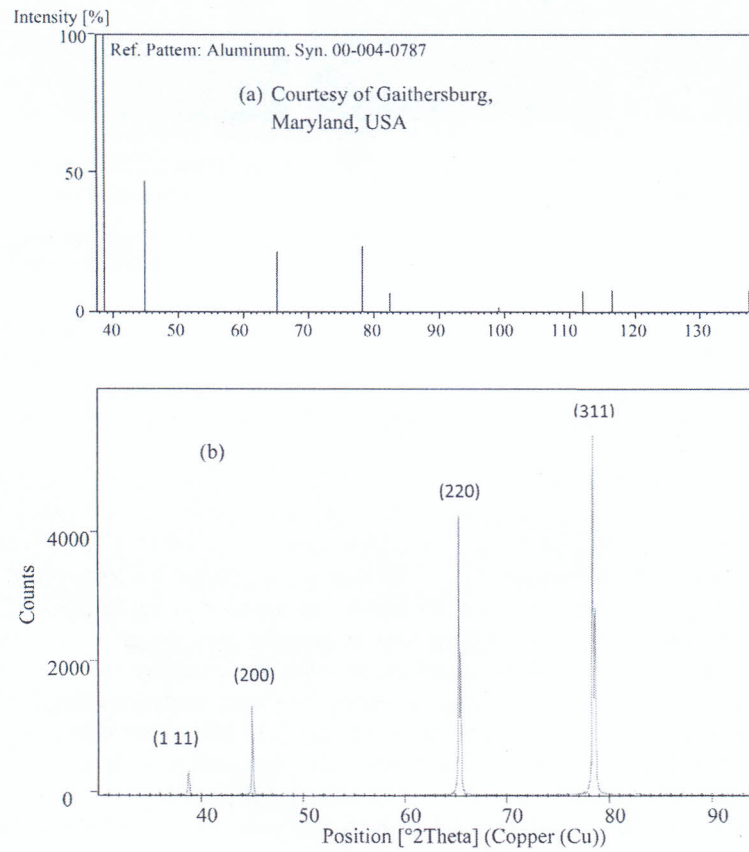


Figure 7. (a) Reference XRD pattern for aluminum (99.99%) obtained from Gaithersburg, Maryland, USA and (b) XRD pattern for cut samples from aluminum sheets.

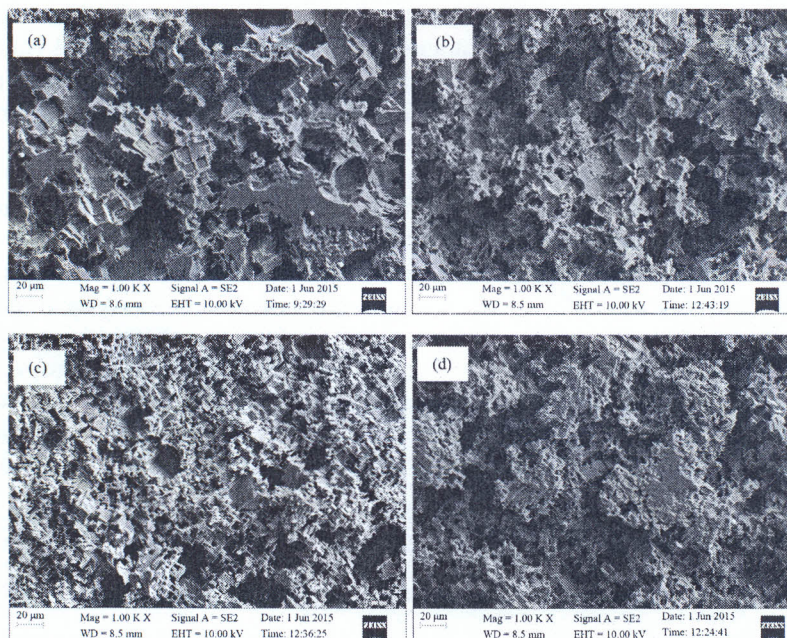


Figure 8. The SEM micrographs showing the pores for different concentrations: (a) undiluted acid; (b) 1:1, acid to ethanol by volume; (c) 1:2, acid to ethanol by volume and (d) 1:3, acid to ethanol by volume.

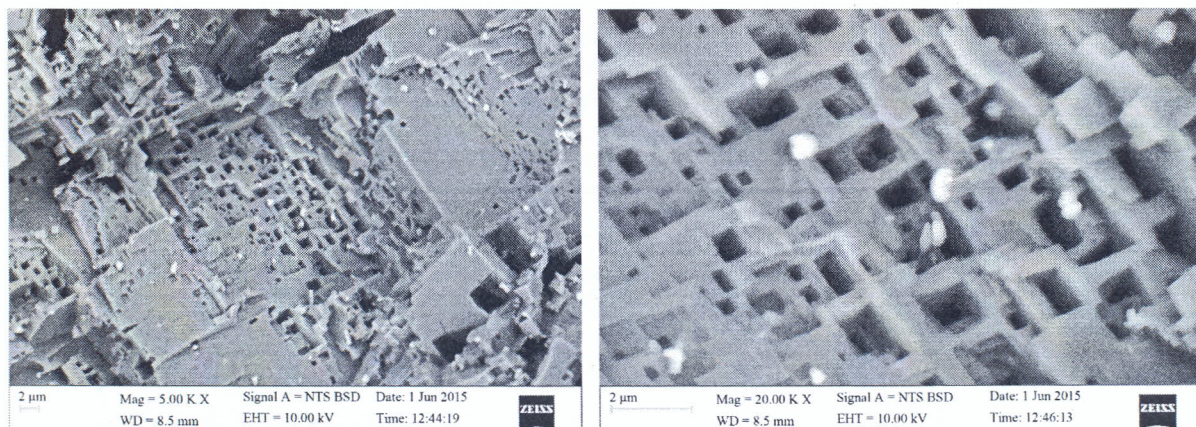


Figure 9. SEM micrograph showing magnified minipores within a bigger pore.

Table 1. EDX analysis of electro-polished aluminum sheet.

Element	Weight%	Atomic%
Al	98.64	99.66
Ag	1.36	0.34
Totals	100.00	100.00

3.4. Optical Analysis

3.4.1. Reflectance of the Polished and Unpolished Aluminum Surface

Reflectance measurements were done for the wavelength range of 300 nm to 2500 nm to corroborate the effectiveness of polishing. As shown in Figure 10, it is observed that the reflectance of polished surface was above 90%. Aluminum is one of the metals that have high reflectance after silver [10]. The over 90% reflectance had also been previously reported by [11]. The unpolished sample recorded a reflectance between 55% to 89% way below the values for polished sample.

There is a general trend of slight decrease in reflectance at shorter wavelength range for the polished surface, but a sharp decrease of reflectance is seen for unpolished aluminum surfaces for wavelength range below 750 nm which is attributed to the fact that shorter wavelength radiation sees much roughness of the surface compared to the long wavelength above 750 nm.

3.4.2. Reflectance of the Etched Aluminum Surface

To achieve pores with the sizes engineered to suit solar radiation absorption, the polished aluminum substrates were textured by controlling the concentration of the etchant, where by, the 1 M perchloric acid was mixed with ethanol in various proportions. The ratios were by volume where 10 ml of 1 M perchloric acid mixed with 10 ml of ethanol is represented as 1:1 ratio. The effect of etchant concentration on the textured samples was studied by taking the reflectance measurements. Figure 11 shows the effect of etchant concentration on the reflectance of the aluminum substrates as indicated in the legend.

In Figure 11, a general decrease in reflectance from longer to shorter wavelengths is seen for every etched sample. This is because longer wavelengths see the textured surface to be smoother compared to short wavelengths and therefore the surfaces are more polished for longer wavelength than for short ones. It is further seen that concentration of the etchant affects reflectance. Samples etched with solution of ratio 1:2 by volume recorded highest reflectance as compared to etchant ratios 1:1 and 1:3. This is attributed to the presence of smaller pores within the larger pores (Figure 9) so that the radiation sees the surface as smooth.

It is evident from Figure 10 and Figure 11 that for polished sample the highest reflectance was about 95% and for textured it was about 69%. It can, therefore be inferred that there was about 26% decrease in reflectance upon texturing or conversely speaking 26% increase in absorption given that aluminum sheet is opaque and does not transmit.

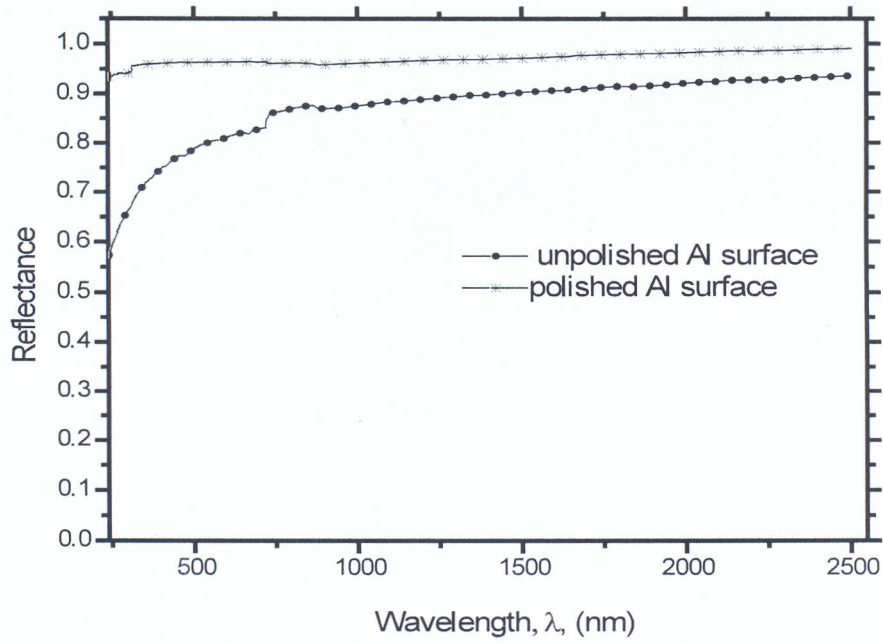


Figure 10. Reflectance spectra for polished and unpolished aluminum surfaces for 300 to 2500 nm wavelength.

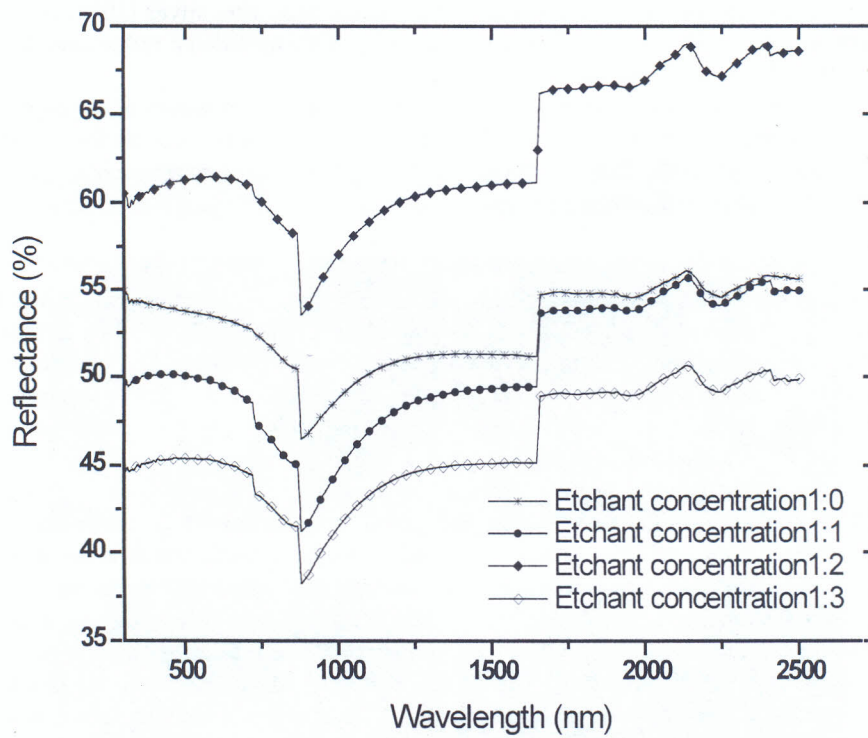


Figure 11. Effect of etchant concentration on the reflectance of the etched aluminum substrates in the spectral range of 300 to 2500 nm.

4. Conclusion

The onset of polishing has been found to be between 10 - 13 V. Aluminum sheet textured in undiluted perchloric acid has been observed to form highly populated large pores of more than 20 μm width, while texturing in di-

luted etchant, concentration is fairly less populated by pores with more than 20 μm wide, majority pore sizes being less than 2 μm . This means that undiluted perchloric acid produces a rougher surface compared to the diluted perchloric acid. This effect is supported by a drop in reflectance or otherwise an increase in absorptance by 26% due to texturing is as a result of porosity and light trapping by the pores. The increase in absorption in the wavelength range of 300 nm to 2500 nm, which represents the bulk of solar spectrum is favorable for solar absorption. Texturing aluminum sheet enhances absorption of the solar radiation. It is, therefore, an adoptable procedure to tailor aluminum sheet as solar energy absorption material. The results have been found to be good for application as a substrate for photo thermal devices.

Acknowledgements

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