

# Macro-study on Hard Anodised Aluminium Oxide (HAAO) Coated Solar Receivers

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**Abstract** This paper is discussing development of Hard Anodized Aluminium Oxide (HAAO) coated Solar Receivers with varying degree of surface roughness and finishing of HAAO coatings for comparative analysis. It is found that for lower DNI, roughness  $R_a < 1.8 \mu\text{m}$  does not adversely impact much on HAAO coating thermal behaviour, but the dark black polished coating may perform better than greyish unpolished surface, therefore high thickness of HAAO coating is desirable  $>150 \mu\text{m}$  using 1000 A rating rectifier (which is limited to 50–60  $\mu\text{m}$  in presented experiment with 400 A rectifier) for further textural developments. Also, their stability at maximum temperature of the focal area of solar concentrators is  $\sim 660 \text{ }^\circ\text{C}$ . HAAO coatings perform better under toughened glass and expected to improve further under vacuum and submerged under water.

**Keywords** Coating · Anodized alumina · Receivers · Absorption · Emission

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## 1 Introduction

**India** is aiming 100 GW of Solar Power by 2022, mainly through PV whereas in future, Solar thermal also being aimed for various applications to get an overall efficiency. This would enable India for partial fulfillment of International Energy Agency (IEA)'s vision 2050 to avoid 2.3 Gt of CO<sub>2</sub> emissions per year.

India has vast solar energy potential of 5000 trillion kWh per year energy with most parts receiving 4–7 kWh/m<sup>2</sup> per day. Due to intrinsic variability nature of solar irradiations, almost all solar thermal and PV systems need selective coatings. Kennedy [1] has reviewed mid to high temperature solar-selective absorber materials in the technical report. The efficiency improvement and cost minimization is to be achieved by increasing the operating temperature of the solar focal area, for which more efficient selective coatings are needed that have both high solar absorptance and low thermal emittance at 500 °C or even higher temperature operation. The coatings need to be stable in air in case the vacuum is not maintained. For efficient photo thermal conversion solar absorber surfaces must have high solar absorptance ( $\alpha$ ) and a lower thermal emittance ( $\varepsilon$ ) at the operating temperature. A low reflectance ( $\rho \approx 0$ ) at cutoff wavelengths ( $\lambda$ ) and a high reflectance ( $\rho \approx 1$ ) at  $\lambda$  characterize spectrally selective coating (SSC). The cutoff may be higher or lower as it is dependent on the temperature [1].

The operational temperature ranges of these materials for solar applications are categorized as low temperature ( $T < 100$  °C), mid-temperature ( $100$  °C  $< T < 400$  °C) and high temperature ( $T > 400$  °C). Parabolic dish concentrators operate at high- and mid-temperatures. The commercial standard of ideal spectrally selective surface would be low cost and easy to manufacture, chemically and thermally stable in air at elevated temperatures ( $T \geq 500$  °C) and have solar absorptance  $\geq 0.95$  and a thermal emittance  $\leq 0.2$  at 500 °C. Many such coatings have been developed in various researches cited in the literature [2], but how much proven are the cited results, in field application, remain unclear at the user end, therefore advised by Kennedy [1] to investigate further for CSP applications.

Kennedy et al. [1–3] has reviewed the selective solar coating materials in depth. AAO Coatings have been mentioned as spectrally selective by Kennedy [1]. Various designs of the solar radiation receivers and SSCs have been discussed in the Solar Publications and Reports but India is still awaiting 'Make in India' drive for the same to get indigenous resourcing of SSCs.

Sergeant et al. [4] has shown high performance solar-selective absorbers using coated sub-wavelength gratings. anodizing.org, almecosolar.com, alanod.com, etc. sites have elaborated various developments in AAO coatings and as SSCs as well.

## 2 HAAO Coating Receivers: Development

In the Kennedy's [1] list of mid-temperature selective coating, Anodized Aluminium Oxide (AAO) coating offers high absorptance up to 0.85–0.97 and also characterizes optimally for selective coating as it has low emittance up to 0.08–0.21, operating in open air mid-temperatures 300–400 °C, hence was focused to develop in present work. Higher temperature AAO coatings are possible with RF Sputtering process when alloyed with Ni, Co, Mo, W and Pt.

If the coating development/application costs too much higher than the return of efficiency enhancement expected, then it may not be commercially viable.

Variety of surface textures were created on the HAAO sample pieces, but the variation in Thermal behaviour in varying Surface Roughness of samples are not so remarkable ( $\sim 1\text{--}2$  °C on single sun at DNI  $\sim 500$  W/m<sup>2</sup>) therefore no specific surface roughness  $R_a < 1.8$  can be suggested as optimal. There is a possibility of inferior performance of the higher roughness as the visible darkness of the AAO surface reduces from black to grey. Although smoother finished AAO coated surface shines more than the rough surface, hence reflect more of the incident solar radiation, but still it performs better than the rough AAO coated surface due to more blackish surface as compared to greyish surface of rough unpolished AAO coated surface. Therefore, it is recommended to apply black AAO coatings even if roughness is to be sacrificed to achieve the same, and best if thicker coating  $\sim 150$   $\mu\text{m}$  or even higher as much as possible is made.

## 3 Comparative Macro-study of HAAO Coatings

Six sample pieces developed for comparative performance based on surface roughness. First sample is of raw Aluminium rolled sheet drawn in saucer shaper without any surface modification. Other five samples are modified at outer and inner surface by emery paper #80 (smoothest available), #120 (course grade hard) and #180 (roughest available) with different combinations as shown in Table 1. That means first sample is just in raw form, the second's outer face made rough with #80 emery paper and inner with #180 emery paper and so on. The darkness as judged visually is marked dark or low with gloss or matt surfaces.

Process parameters for coating development are shown in Table 2. After roughness, all the six samples were coated with hard anodized coating and compared for surface temperatures attained in exposing outer surface to the Sunlight as shown in Table 3 for Macro-Study.

From Table 3, it is evident that the maximum temperature is mostly attained by sample #2 and 3; both are smoother in outer surface as compared to the other samples, although there is no remarkable difference in the temperatures attained by all the samples, it implies that the maximum temperature can be attained by some degree of roughness on the surface. The raw Aluminium rolled sheet when drawn in

**Table 1** AAO coated samples of varying surface textures (roughness)

Sample #	1	2	3	4	5	6	Weight
Outer emery #	X	80	80	120	180	180	425 g
Inner emery #	X	180	80	180	80	180	(Each)
$R_a$ outer face	0.5207	0.5074	0.8359	0.751	1.4598	1.1541	(Telisurf)
$R_a$ inner face	1.1097	4.3233	1.6022	2.243	3.785	3.3657	(Telisurf)
Darkness	Dark grey	Dark matt	Dark matt	Low	Low	Low	Visual

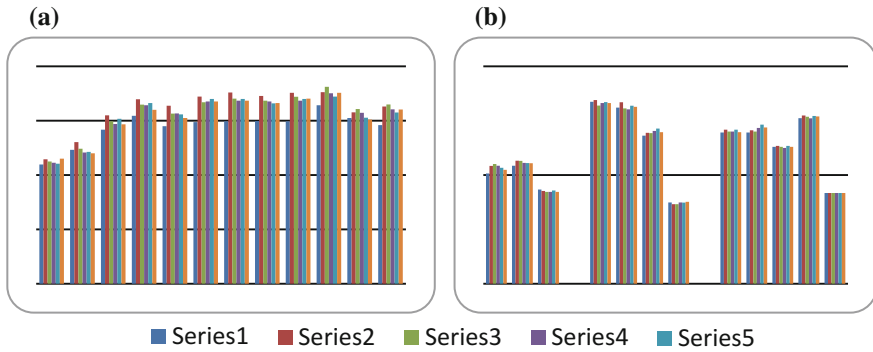
**Table 2** AAO coated samples development anodizing process parameters

Rectifier current	400	A
Rectifier voltage	80	VDC
Oxalic acid	10	%
Sulphuric acid	15	%
Time retained	3	Hours approx (for 55–60 $\mu\text{m}$ coating)
Bath temperature maintained	-2	$^{\circ}\text{C}$
Aluminium sheet thickness	3.15	mm

**Table 3** Surface temperatures of samples under direct Sun on a sunny day

Time	1	2	3	4	5	6	Time	1	2	3	4	5	6
08:30	43.9	45.8	45	44.5	44.2	46	16:47	54.3	56.6	56.5	55.6	55.5	55.4
09:00	49.3	52.1	49.7	48.3	48.5	48	17:30	43.3	42.7	42.2	42.2	42.9	42.2
09:36	56.7	62	59.8	58.8	60.7	58.7							
10:00	61.8	67.9	65.9	65.7	66.5	64	13:45	83.7	84.5	82	83.1	83.6	83.1
10:30	58	65.5	62.6	62.7	62.3	61	14:30	81	83.5	80.7	80.2	81.9	81.4
11:00	59.5	68.9	66.8	67.1	68	67.1	15:15	68.1	69.4	69.3	70.3	71.4	69.7
11:30	59.8	70.4	68.1	67.4	68	67.4	20:15	37.4	36.6	36.6	37.4	37.3	37.7
12:00	59.9	69.1	67.4	67.1	66.4	66.5							
12:30	59.8	70.3	68.8	67.4	68	68.1	09:45	69.6	70.9	70	70	70.9	69.7
13:23	65.7	70.5	72.5	70.1	68.9	70.3	12:20	69.6	70.6	70	71.7	73.2	71.9
14:45	61	63.1	64.3	62.9	61.1	60.4	13:35	63	63.4	63	62.5	63.4	63
15:15	58.4	65.2	66	64.2	63	64.1	14:45	76.2	77.4	76.8	76.1	77.2	77
16:00	50.7	54.2	55.1	54.3	53.3	52.4	20:45	41.7	41.7	41.7	41.7	41.7	41.7

the die, becomes very glossy (high  $\rho \gg 0$ ) hence there is lesser solar energy collection on the surface, even when the darkness of the coated film on the surface is maximum, i.e. higher absorptance. The sample #2 and #3 are nearly darker to sample #1, but due to the surface roughness, these have become matt instead of remaining glossy hence lesser reflectivity is possible in these samples which retain more solar radiation hence better surface temperature. With this reason, sample #4, 5 and 6 should have gained higher temperatures as they are more rougher than #1, 2 and 3 but it is not happening so because of the fact that darkness of the film is



**Fig. 1** a, b Comparative performance of HAAO receiver samples 1–6 at different solar radiations in a day (X-axis time in hours and Y-axis temperature in °C)

getting reduced in these samples due to lesser penetration of the coating under the surface. This can be improved with the use of 1000 A rating rectifier, for developing thicker coating of AAO.

On other days, sample #5 and 6 also attained higher temperature equally comparable with sample #2; during non-peak DNI hours, therefore roughness has impact on absorptance of the AAO coating at lower DNIs but at higher DNI and higher concentration ratio, it is not necessary to impart high surface roughness on AAO coating. Emery paper #80 would be enough to improve the solar absorptance. The same observation can be better seen in Fig. 1.

Since the rectifier’s highest current rating  $\sim 400$  A have been used, therefore more thicker coating above  $60 \mu\text{m}$  is possible only at 1000 A rating Rectifier, which was not available during this project schedule, therefore the same can be taken up in future developmental work.

After AAO coating, polishing operation is possible on AAO coating, which reduces surface roughness and improves darkness. Improving darkness would give better solar radiation collection efficiency but the reduced roughness would also increase the emittance hence net gain in solar radiation can be optimized by striking balance in roughness, coating thickness and polishing operations.

To test the effect of polishing, three other samples of varying polish exposed to Sunlight, observations recorded in Table 4.

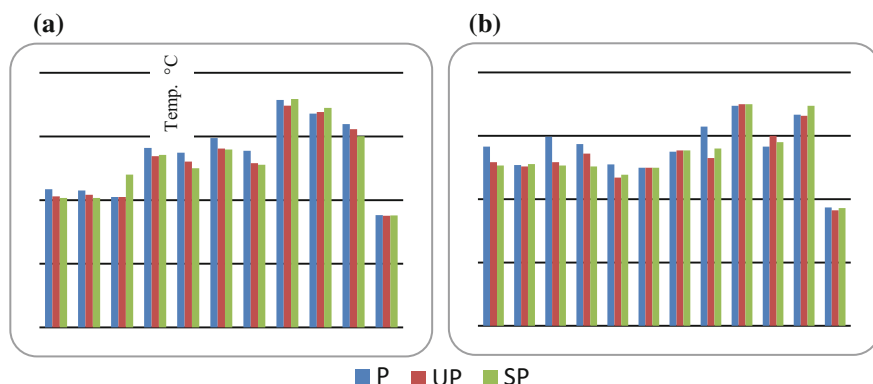
Although in Table 4 and Fig. 2, mixed trend is being observed on different days. In graphical representation, it is observed that no much appreciable difference in polished versus unpolished/semi polished surface existing, therefore it can be concluded that choice of polishing the AAO surface as finished product may be dropped to reduce the cost of the process as well to reduce the reflection of the incident radiation.

To compare the effect of anodizing along with glass casing, four samples chosen, First of MS plate, Second of Plain Aluminium, Third of Anodized, outer surface polished and inner surface unpolished without surface roughness development kept

**Table 4** Effect of polishing after anodizing process on AAO surface

Time	P	UP	SP	Time	P	UP	SP	Time	P	UP	SP
08:30	43.4	41.2	40.7	14:30	67.2	68	69	16:47	49.9	49.9	49.9
09:00	43	41.7	40.7	15:15	63.9	62	60.1	17:30	55	55.4	55.4
09:36	41	41	48	20:15	35.3	35	35.2	09:45	62.9	53	56
10:00	56.4	53.8	54.2	10:30	56.6	52	50.6	12:20	69.5	70	70
12:30	54.9	52.1	50	11:00	50.8	50	51.1	13:35	56.6	60	58
13:23	59.5	56.2	55.9	11:30	59.7	52	50.6	14:45	66.7	66.3	69.5
15:15	55.5	51.6	51.1	12:00	57.4	54	50.3	20:45	37.4	36.5	37.2
13:45	71.5	69.7	71.8	16:00	51	47	47.7	09:45	62.9	53	56

*P* Polished; *UP* unpolished; *SP* semi polished



**Fig. 2** a, b AAO coating performance—different polishing surfaces

in open direct contact with atmosphere and last sample also same as third one but kept inside a glass casing. All were kept under sunlight and observations recorded as in Table 5.

For analysis, in Fig. 3 of Table 5 data shows a general trend of increasing surface temperature from Aluminium to MS plate to open AAO to encased AAO surfaces. This implies that for Solar thermal applications it is better to replace MS plate receiver with AAO surface, preferably under a Glass casing.

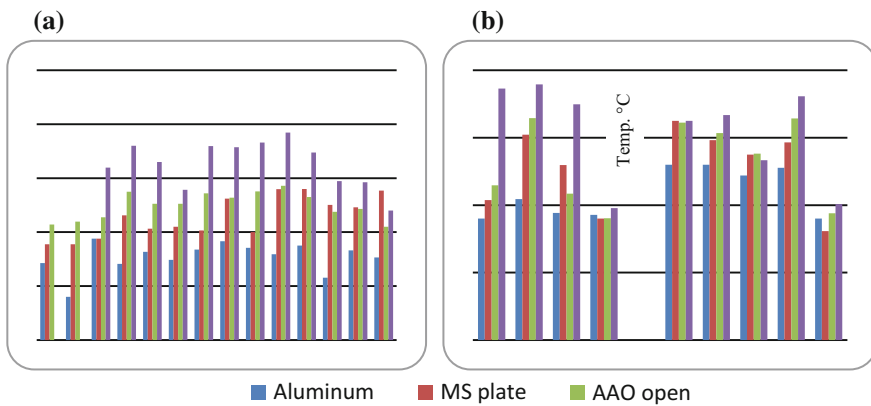
If complete casing of the AAO surface inside glass is not feasible at site, possibility can be to only cover up the face of AAO coating with Glass Sheet, which should be toughened to sustain higher temperatures of the AAO surface at the focal area of solar radiation receiver or concentrators.

The samples used to experiment are shown in Fig. 4. All temperatures recorded with infrared thermometer of range  $-30$  to  $+500$  °C with an accuracy of  $\pm 3$  °C. It is desirable to use a higher accuracy thermometer for above experiments to arrive on more accurate results; otherwise these experiments may also be done on higher concentration ratios for wider difference in temperature range of the samples. With

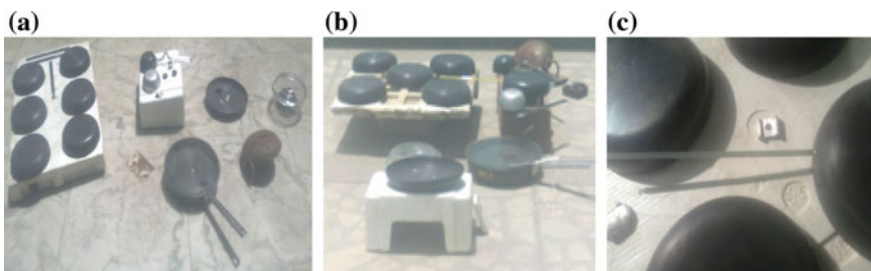
**Table 5** Effect of anodized coating on surface with casing inside glass

Time	Al	MS	AAOA	AAOG	Time	Al	MS	AAOA	AAOG
8:30	28.5	35.5	42.8		16:47	33.2	49.2	48.6	58.5
9:00	16	35.5	43.9		17:30	30.6	55.4	42	48
9:36	37.6	37.6	45.5	63.9	13:45	36	41.5	45.9	74.6
10:00	28.2	46.2	55	72	14:30	41.8	60.9	65.8	75.8
10:30	32.7	41.3	50.5	66	15:15	37.7	51.9	43.4	69.9
11:00	29.7	42	50.5	55.7	20:15	37.1	36	36.1	39.1
11:30	33.5	40.6	54.4	71.9					
12:00	36.6	52.4	52.8	71.5	9:45	52	65	64.5	65
12:30	34.2	40	55.1	73.2	12:20	52	59.3	61.4	66.7
13:23	31.8	55.9	57.2	76.9	13:35	48.8	55	55.3	53.3
15:15	35	56	53	69.5	14:45	51.1	58.6	65.7	72.3
16:00	23.1	50.1	47.5	58.9	20:45	36	32.3	37.6	40.3

Al Aluminium; MS mild steel; AAOA AAO in air; AAOG AAO in glass



**Fig. 3** a, b Anodized coating on surface with casing inside glass



**Fig. 4** a, b, c Photographs of samples developed

16 m<sup>2</sup> Scheffler dish, it has been observed that without heat transfer from the coating surfaces, the substrate metal, i.e. Aluminium gets melted instantaneously ~660 °C but HAAO Coatings remains stable.

## 4 Results and Discussion

Indigenous HAAO coatings developed for low and mid-temperature applications. The AAO coatings should be at least 55–60 µm thick and may be given surface roughness with emery paper #80 for better performance. After anodizing, polishing may be a choice of aesthetics but it may or may not improve performance unless coating is developed thicker ~150 µm for which rectifier rating MCR should be ~1000 A, of commercial grade.

The glass covers can be applied with anti-reflection coating for highest solar absorption together with lower thermal emissivity. The glass should be toughened for sustaining higher temperatures. If the process operational temperature is below 200 °C, then carbon black or powder coating can also be applied for better absorptive properties.

Minimum diameter of Aluminium flat disc needed was 280 mm. Below this, AAO coatings are not enough 55–60 µm thick and hence getting peeled off therefore not stable. Also, it is found that more surface roughness of Ra > 1.8 µm is resulting in poor AAO coating development and its stability as it peels off very soon from the sharp peaks and valleys of the surface.

Tests may be conducted on-site in actual weather conditions with varying heat generation as well as varying system load/demands, to select the optimum.

## 5 Conclusion

Hard anodized Aluminium coatings may offer a better option for solar thermal applications up to 500 °C, making them selective optically by integrating with anti-reflection coated suitably toughened glass and water submerged absorbers. Results suggest improving receiver efficiency by ~10–15% over the uncoated MS plate surfaces along with better stability at elevated temperatures. The cost of AAO receiver may be justified over the conventional MS receiver with any other coating, in fact in mass production; it may be equally competitive with MS receivers with any other type of coatings.



## 6 Future Prospects and Suggestions

Thicker HAAO coating with vacuum glass shields may be further experimented with higher solar radiation concentration ratio; to arrive on solutions for high temperature applications. There was limited time period for which the data collected and analyzed. It can be done over a year for a particular location, so that better conclusion for exact specifications of particular type of coating selection can be drawn up. HAAO solar receivers can relieve parabolic dish users from the corrosion and erosion troubles being faced with conventional receivers, in addition to enhance the energy efficiency of the solar receivers.

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