METHODS FOR SERVICE LIFE TIME ESTIMATION OF ALUMINUM REFLECTORS

Florian Sutter[1], Peter Heller[1], Aránzazu Fernandez-García[2], Cheryl Kennedy[3], Rafael López-Martín[2], Stephanie Meyen[1], Robert Pitz-Paal[4]

[1] DLR German Aerospace Center, Institute of Solar Research, PSA, Ctra. Senés Km. 4, P.O.Box 44, 04200, Tabernas, Almería (Spain), +34 950 277 684, Florian.Sutter@dlr.de

[2] CIEMAT, Plataforma Solar de Almeria (PSA), Ctra. Senés Km. 4, 04200 Tabernas, Almería (Spain)

[3] NREL National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401-3393 USA

[4] DLR German Aerospace Center, Institute of Solar Research, Linder Höhe, D-51147 Cologne, Germany

Abstract

In order to reduce electricity generation costs of concentrating solar power (CSP) technologies, new low-cost reflector materials are being developed. These materials need to withstand difficult outdoor conditions without a significant loss in specular reflectance. In this work, samples of enhanced anodized aluminum reflectors protected by a sol-gel coating exposed at different weathering sites have been analyzed with an innovative specular reflectometer and accelerated aging tests have been carried out in order to estimate the service life time. A new accelerated aging procedure is proposed, which consists in combining abrasion and corrosion testing.

Keywords: accelerated and outdoor weathering, aging of solar reflectors, specular reflectance, reflectometer, filiform corrosion of aluminum

1. Introduction

Concentrating solar power (CSP) plants commonly use thick-glass silvered mirrors to reflect and concentrate direct sunlight onto an absorber. The reflector cost for all three CSP technologies (parabolic troughs, central towers, and parabolic dishes) represents about 30% of the collector cost [1]. In order to achieve competitive electricity generation by solar energy, it is desirable to replace the expensive thick-glass mirrors with low-cost reflective surfaces. These new materials must demonstrate that they can withstand outdoor conditions without a significant loss of specular reflectance for more than 20 years. Quick and reliable methods to test the durability of reflector materials are needed in order to reduce the investment risk for CSP plants.

The commonly used accelerated aging tests usually involve exposure to corrosive atmospheres, increased UV radiation, thermal cycling or simulation of abrasive effects. These durability tests have been adapted from other industries for solar reflectors. However, development of testing procedures that allow reliable service lifetime predictions to be made for solar reflectors is in its infancy. This paper is focused on developing a suited accelerated aging test procedure for aluminum solar reflectors.

2. Methodology

Enhanced first-surface aluminum mirrors are anodized 0.5-mm-thick polished aluminum substrate coated with 65-nm-thick pure aluminum layer deposited by physical vapor deposition (PVD). The reflectance of the aluminum is enhanced by ¼-wavelength (λ) thick low-index (75-nm SiO_2) and high-index (55-nm TiO_2) refraction oxide coatings. The coating stack is protected by a (3-µm SiO_2) sol-gel nanocomposite oxide layer.

Three types of tests were carried out in order to estimate the specular reflectance losses of enhanced aluminum reflectors: outdoor weathering tests at different exposure sites, outdoor exposure of samples without protective top coating and accelerated aging tests.

The degradation of the tested samples was examined using microscopy and they were optically analyzed with a newly developed reflectometer, *(SR)²,* which enables the specular reflectance to be measured at different acceptance angles [2]. The system is based on a photographic method that allows the reflectance characteristics of flat mirrors to be evaluated at any point on its surface. It has a spatial resolution of 37 pixel/mm and a precision of ±0.6% at 12.5mrad acceptance half-angle.

Samples of the enhanced aluminum reflector have been exposed at four different sites for up to 5 years. The analysis of the weathered samples showed that losses in specular reflectance are mainly due to two degradation mechanisms: filiform corrosion processes at the aluminum layer underneath the protective coating [2] and optical scattering at the top coating.

The commonly used standardized accelerated tests (e.g. ISO9227, ISO11341, ISO3665, ISO6270-2CH) do not reproduce the same degradation mechanisms observed at the outdoor weathering sites of the aluminum reflector. For that reason, a new accelerated aging procedure for aluminum reflectors is being proposed that should simulate 10 years of outdoor exposure.

Samples of the enhanced aluminum reflector without the protective top coating have been exposed in order to monitor quick degradation in real outdoor environments. The microscope images in Figs.1 and 2 show that the appearance of the corrosion of the coated and uncoated samples are very similar, thus, assumptions about the service life time of the coated samples are based on the degradation of uncoated samples.

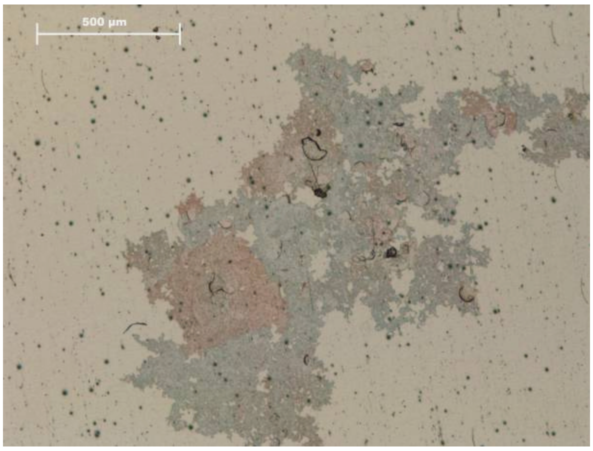

Fig. 1. Filiform corrosion of enhanced aluminium reflector after 59 months of outdoor exposure in Tabernas, Spain.

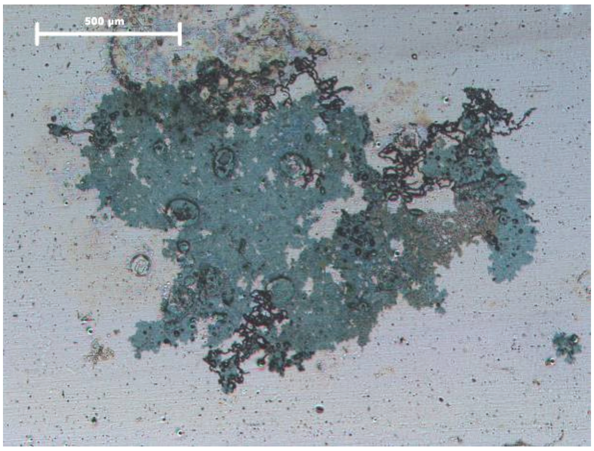

Fig. 2. Filiform corrosion of enhanced aluminium reflector without protective coating after 6 months of outdoor exposure in Almeria, Spain.

3. Outdoor weathering

Enhanced aluminum samples that have been exposed to environmental conditions at several outdoor weathering sites have been analyzed as well as additional samples especially prepared without the protective sol-gel coating. The results permitted to develop a service life time estimation model.

3.1 Analysis of weathered samples

The newly developed space-resolved specular reflectometer (*SR)²* is especially employed to detect and monitor filiform corrosion processes of the outdoor exposed aluminum reflector samples. Fig. 3 shows the corroded surface percentage, f_c, of outdoor weathered samples at four different exposure sites, under a variety of climates and stress conditions.

For the samples without protective coating the time dependency of the corroded surface percentage due to filiform corrosion f_c can be approximated by an Avrami-distribution:

$$f_c(t) = 1 - \exp(-k \cdot t) \tag{1}$$

where t is the time in months and k the Avrami constant. The Avrami equation is generally used to describe the kinetics of phase changes in materials. The fit according to the Avrami distribution showed to approximate best to the measured data.

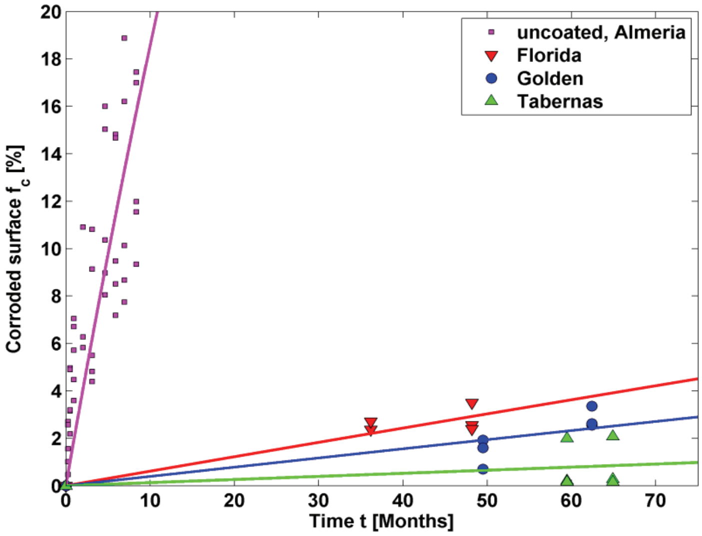

Fig. 3. Corroded surface percentage f_c of various weathered aluminium reflector samples.

Similar degradation mechanisms occur for coated and uncoated samples, therefore it was assumed that the corrosion kinetics of the coated material will also follow an Avrami-distribution. However, the coating quality and the environmental conditions at the exposure site will determine the Avrami constant. Table 1 shows the Avrami constants k obtained by applying a least square fit to the measured data (see Fig. 3), as well as the estimated corroded surface percentage after 10 years (120 months) of exposure, $f_{c,120}$, at each site. The corroded surface still reflects part of the incident light although the specular reflectance suffers a significant drop. The average specular reflectance of the corroded surface was measured with the space-resolved reflectometer (*SR)²* and it showed to be ρ_c=41.7% in average for coated and uncoated samples at various exposure sites. ρ_c showed to decrease only slightly over time and is therefore regarded as constant. With this approximation, the specular reflectance loss after 10 years of exposure due to corrosion, $\Delta\rho_{c,120}$, has been estimated and the values are also shown in Table 1. $\Delta\rho_{c,120}$ is computed using the following equation:

$$\Delta\rho_{c,120} = f_{c,120} \cdot \left(\rho_{initial} - \rho_c\right) \tag{2}$$

where $\Delta\rho_{c,120}$ is the specular reflectance loss after 10 years of exposure due to corrosion, $f_{c,120}$ is the estimated corroded surface percentage after 10 years of exposure, $\rho_{initial}$ is the initial specular reflectance ($\rho_{initial}$ is 83.5% for coated samples and 86.5% for uncoated samples) and ρ_c is the constant specular reflectance of the corroded surface (ρ_c=41.7%).

Exposure site	**Coating**	***k* [1/months]**	**$f_{c,120}$ [%]**	**$\Delta\rho_{c,120}$ [%]**
Almeria, Spain	uncoated	$2.23 \cdot 10^{-2}$	93.1	41.7
Tabernas, Spain	Coating A	$1.31 \cdot 10^{-4}$	1.6	0.7
Florida, USA	Coating A	$6.15 \cdot 10^{-4}$	7.1	3.0
Golden, USA	Coating A	$3.92 \cdot 10^{-4}$	4.6	1.9

Table 1. Avrami constants, *k,* for different coatings and exposure sites, estimated corroded surface percentage after 10 years of exposure, $f_{c,120}$, and estimated reflectance loss after 10 years due to corrosion, $\Delta\rho_{c,120}$

The (*SR)²* has also been used to analyze the reflectance characteristics of the percentage of surface that was unaffected by fliliform corrosion. Fig. 4 shows the losses in specular reflectance of the non-corroded surface, ρ_{nc}, for different coated reflector samples exposed outdoors.

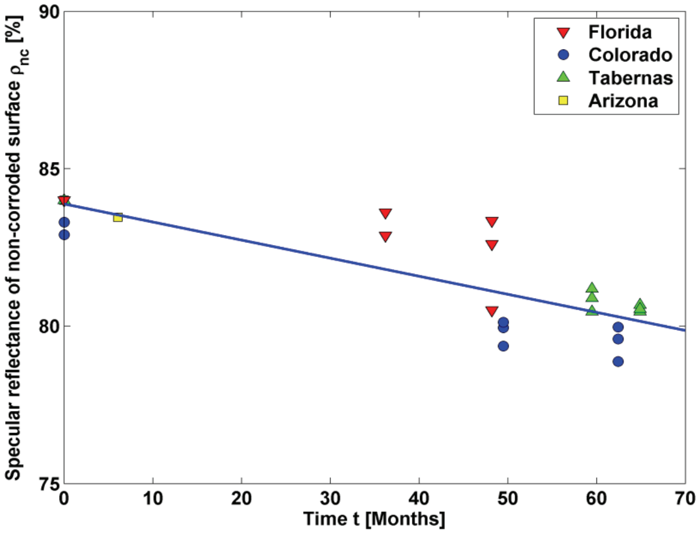

Fig. 4. Specular reflectance of non-corroded surface, ρ_{nc}, during exposure at various sites.

The specular reflectance – time dependency is approximated as a linear decay:

$$\rho_{nc;656nm;15°;12.5mrad}(t) = \rho_{initial} - k_s \cdot t = 83.5\% - 0.057\frac{\%}{months} \cdot t \tag{3}$$

where $\rho_{nc;656nm;15°;12.5mrad}$ is the specular reflectance of the non-corroded surface measured at 656nm and 15° incidence angle and 12.5mrad acceptance angle, $\rho_{initial}$ is the initial specular reflectance and k_s is the constant for optical scattering which depends on the coatings resistance to abrasion.

Due to the high deviations, the best fit line is not evaluated for each exposure site. It gives a rough idea that optical scattering at the non-corroded reflector surface leads to a specular reflectance loss of approximately 6.8%±2% in 10 years. Hence the specular reflectance of the non-corroded surface after 10 years of exposure will be around $\rho_{nc}(120\ months) = 76.7\%$.

Losses in specular reflectance at the non-corroded surface can appear due to blowing particles (sand or dust) or soiled particles that cannot be removed with conventional cleaning methods. Some coating-defects also appear during manufacturing or transport of the samples before they are exposed to the outdoor environment. Fig. 5 shows microscope images of a new sample, compared to a sample exposed for more than 5 years outdoors at the Plataforma Solar de Almeria (PSA) in Tabernas, Spain. It can be observed that the number of coating defects has increased, which results (together with other possible effects) in a reflectance loss of about 3.7%.

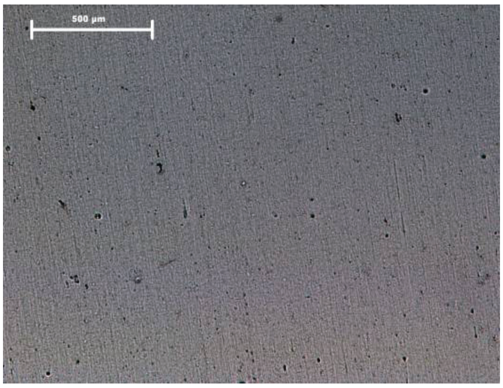

Fig. 5a) new, non-aged material, $\rho_{660nm;\ 15°;12.5mrad} = 85.2\%$.

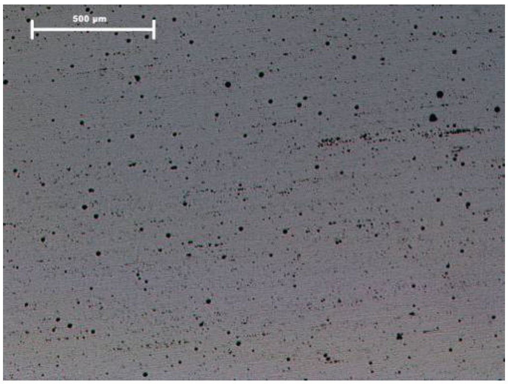

Fig. 5b) after 64 months of outdoor exposure in Tabernas, Spain, $\rho_{660nm;\ 15°;12.5mrad} = 81.5\%$.

3.2 Service life time estimation

Based on the previously shown outdoor exposure data, a model to estimate the service life time was derived. It estimates the specular reflectance $\rho_{656nm;15°;12.5mrad}$ at 656nm wavelength, 15° incident angle, and 12.5mrad half-cone acceptance angle as a function of time by taking into account both the degradation caused by optical scattering and the reflectance losses due to corrosion. The dependency of the degradation on the exposure site is introduced by the use of the local Avrami constant from Table 1.

$$\begin{aligned}\rho(t) &= \rho_{initial} - \Delta\rho_c(t) - \Delta\rho_S(t)\\ &= \rho_{initial} - f_c\cdot(\rho_{initial}-\rho_c) - (1-f_c)\cdot(\rho_{initial}-\rho_{nc})\\ &= \rho_{initial} - (1-\exp(-k\cdot t))\cdot(\rho_{initial}-\rho_c) - \exp(-k\cdot t)\cdot k_S\cdot t\end{aligned} \tag{4}$$

where $\Delta\rho_c$ and $\Delta\rho_S$ are the reflectance losses due to corrosion and optical scattering, k is the site dependent Avrami constant and k_s is the site independent constant for optical scattering. For the tested protective coating k_s is equal to 0.057%/months. The specular reflectance of the corroded surface ρ_c is considered to be a constant 41.7%, independent of the exposure site and the coating type.

New improvements to the protective coatings have the potential to reduce the Avrami constants. However, so far there is insufficient outdoor exposure data available to be able to make well-founded declarations about the performance of the new coatings.

The specular reflectance over time for the exposed aluminum reflectors is shown in Fig.6. The measurements are compared to the service life time estimation model (equation 4). The dashed line in the graph represents the initial specular reflectance of the mirror. The overall reflectance loss ($\Delta\rho_c + \Delta\rho_S$) is indicated in Fig.6 for the site of Florida.

The model predicts reflectance losses in the range of 7.4 to 9.3% after 10 years of weathering, depending on the exposure site.

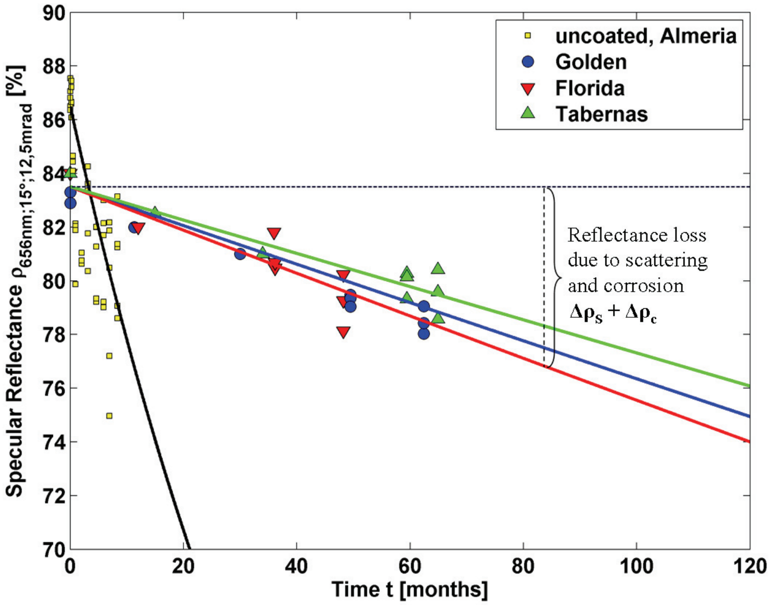

Fig. 6. Specular reflectance at various exposure sites and service life time estimation model.

4. Accelerated aging testing

In order to determine the durability of recently developed coatings, it is desirable to quickly evaluate their expected performance in outdoor conditions. Therefore an accelerated test procedure is presented that allows estimating the constant for optical scattering k_s and the Avrami constant k.

4.1 Optical scattering at the top coating

The wind tunnel of PSA, shown in Fig. 7, has been used to reproduce the optical scattering effect. It is a closed circuit chamber that enables the injection of dust particles into the circulating airflow. It is capable to operate at dust concentrations up to 2.5 g/m³ and wind speeds up to 30 m/s. The standardized Arizona Road Dust (ARD) (A4 coarse grade) according to SAE J726 is used.

Testing was performed with four aluminum samples at 3.0, 4.7, 5.5 and 8.0 m/s and a dust concentration of 500 mg/m³.

As it is not always possible to control the concentration to obtain exactly 500 mg/m³, an equivalent exposure time, t_e, was calculated according to the following formula:

$$t_e = t_{real} \cdot \frac{c_{avg}}{500\,mg/m^3} \qquad (5)$$

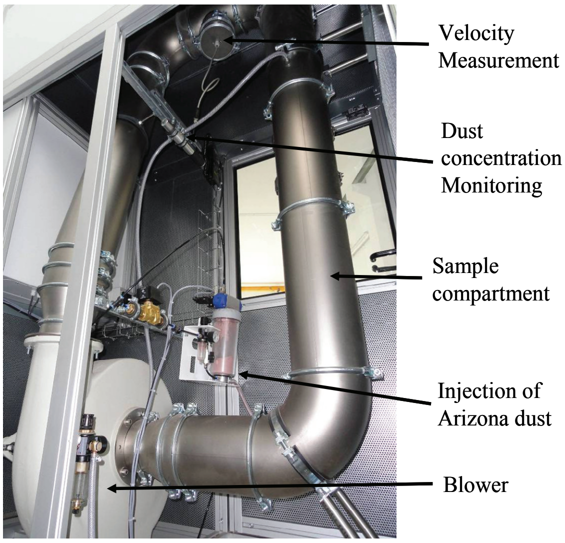

Fig. 7. Wind tunnel at PSA

t_{real} denotes the real duration of the test and c_{avg} the average dust concentration in mg/m³ during t_{real}. This correction accounts for concentration deviations from the set point that was in the range of ±100mg/m³. This concept is reasonable because a sample exposed for the same time and velocity but twice the concentration showed to degrade twice as fast.

The specular reflectance losses of the four tested samples in the wind tunnel are shown in Fig. 8. The reflection losses can be approximated by a linear decay for all wind speeds. The time to simulate optical scattering of 10 years of outdoor exposure (the time needed to reach $\rho_{nc,120} = 76.7\%$) is shown in Table 2. By comparing the linear decay from real outdoor conditions (see Fig. 4 and formula 2) with the measured linear slopes from Fig. 8, the acceleration factor of the test can be determined. The acceleration factor can be employed to evaluate the constant for optical scattering k_s for different coatings.

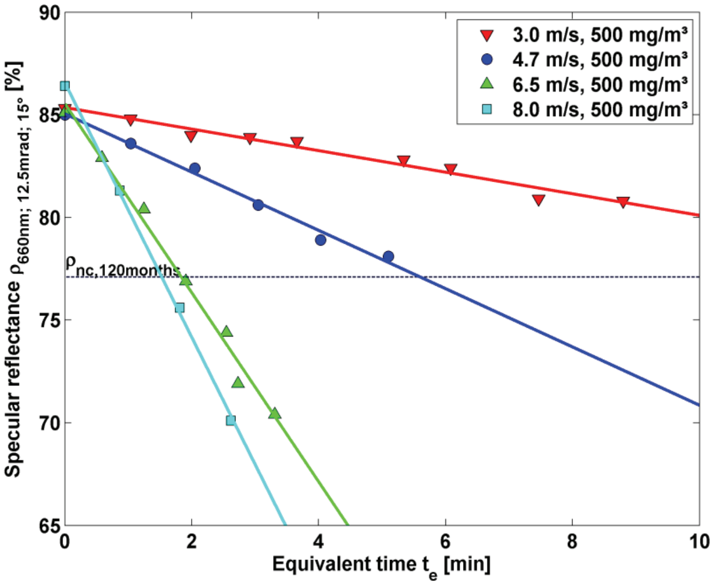

Fig. 8. Specular reflectance of samples aged in the PSA wind tunnel at 500 mg/m³ and different wind speeds.

Wind speed [m/s]	Time t to reach $\rho_{nc,120}$ [min]	Acc. factor
3.0	15.6	$3.3 \cdot 10^5$
4.7	5.6	$9.2 \cdot 10^5$
6.5	1.8	$2.9 \cdot 10^6$
8.0	1.5	$3.5 \cdot 10^6$

Table 2. Acceleration factor and testing time to simulate the optical scattering of 10 years of outdoor exposure at 500 mg/m³ and different wind speeds in the PSA wind tunnel.

Microscope images of two samples aged in the wind tunnel are shown in Fig. 9. Ten years of outdoor exposure have been simulated at a wind velocity of 4.7 m/s in Fig. 9a) while Fig. 9b) intends to reproduce the optical scattering observed at PSA after 64 months of outdoor exposure with a wind velocity of 6.5m/s. The microscope images show a good agreement in the number of coating defects (compare Fig. 5b with Fig. 9b) but it is unclear if the severity or depth of the defects is also similar. Therefore, the coatings of several samples have been damaged at different wind speeds, and a corrosion test was performed afterwards. The most realistic corrosion pattern has been identified at the lowest wind speeds. However, at low wind speeds it is harder to keep a constant dust concentration in the wind tunnel. Further testing was performed at 4.7 m/s, which is a good compromise between the two.

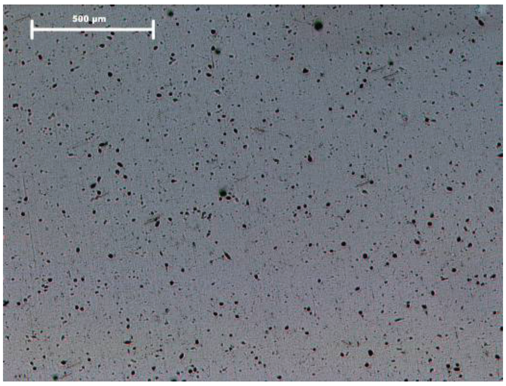

Fig. 9a) after 5 minutes of exposure to ARD at 4.7 m/s and 582 g/m³, $\rho_{660nm;\ 15°;\ 12.5mrad}=78.3\%$.

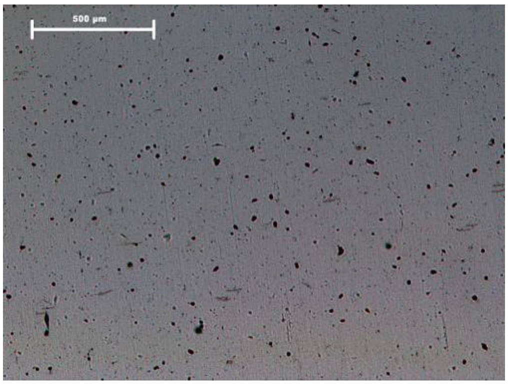

Fig. 9b) after 1 minute of exposure to ARD at 6.5 m/s and 619 g/m³, $\rho_{660nm;\ 15°;\ 12.5mrad}=80.9\%$.

4.2 Filiform corrosion

Filiform corrosion is a type of localized corrosion that appears as thread-like filaments underneath coatings. It is known to appear in areas of high humidity (>65% relative humidity) especially when chloride ions are present, and always starts at defects in the protective coating [3], [4]. Therefore, the proposed accelerated test method involves pre-damaging the sol-gel coating in the wind tunnel and afterwards performing the neutral salt spray test (NSS) according to ISO 9227 [5]. The NSS-test is one of the corrosion tests used by the solar mirror manufacturers. It consists of exposing the samples in a chamber while spraying a sodium-chloride solution of 50 g/l at a temperature of 35°C. The test duration depends on the protective coatings; typically the mirror industry performs the test for 480 hours.

The loss in specular reflectance during exposure to the NSS-test for pre-aged samples in the wind tunnel and for new samples is shown in Fig.10. The samples were pre-damaged by 5.6 minutes of exposure to 500 mg/m³ of ARD blown in the wind tunnel at 4.7 m/s. The data can also be approximated by an Avrami distribution. The high deviations in the measured data are due to the complexity of the corrosion process, which may result in poor repeatability. The degradation is also influenced by the position of the sample in the chamber because it is not always possible to get a completely homogeneous distribution of the salt fog in the testing cabinet.

The reflectance loss due to corrosion was observed to occur at a faster rate when the protective coating was pre-damaged. Ten years of outdoor weathering in Florida was simulated by 400 hours of the NSS test for pre-damaged samples. The acceleration factor is estimated to be 220 times faster compared to samples exposed in Florida for pre-damaged samples and 95 times faster for new samples. These acceleration factors can be used to make estimates of the Avrami constants of other protective coatings depending on their performance in the NSS-test.

The appearing corrosion mechanism observed in the NSS-test differs considerably from the filiform corrosion found outdoors. However, 400 hours of the NSS-test lead to the same reflectance loss, even though different corrosion processes are happening. The NSS-test showed the most proximate alikeness to the corrosion outdoors and is therefore considered to be the best suited test within the actually available standardized tests. However, to increase the reliability of the accelerated aging procedure in the future, the NSS-test should be replaced by a corrosion test that reproduces the observed filiform corrosion from outdoors in a more realistic way.

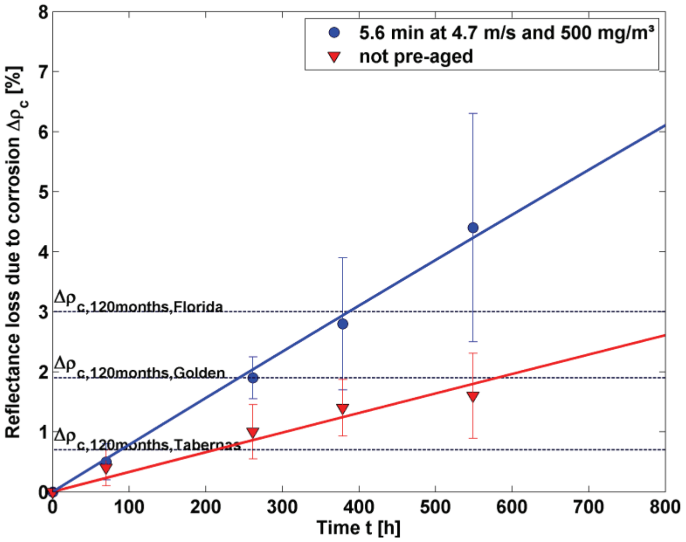

Fig. 10. Specular reflectance loss, $\Delta\rho_c$, due to corrosion in the Neutral Salt Spray Test according to ISO9227 of new and pre-aged aluminium reflector samples in the PSA wind tunnel.

5. Conclusions

The specular reflectance properties of enhanced aluminum reflectors weathered outdoors were shown to suffer from two degradation mechanisms: optical scattering at the top coating and filiform corrosion at the aluminum layer. The effect of those two degradation mechanisms on the specular reflectance has been analyzed with the space-resolved specular reflectometer for various outdoor weathered samples. The results permitted a service life time estimation to be derived, which was used to develop an accelerated aging test procedure. The surface scattering effect was reproduced by exposing the samples to blowing dust in a wind tunnel. Afterwards the pre-damaged protective coating samples were subjected to the neutral salt spray test. It was found that pre-damaging the sample for 5.6 minutes at 4.7 m/s and 500 mg/m³ of blowing ARD and posterior exposure of approximately 400 hours to the NSS-test can be correlated to 10 years of outdoor weathering in Florida for enhanced aluminum reflectors. The found test conditions may be used to estimate the service life time of similar aluminum reflectors that suffer from the same degradation mechanisms.

Acknowledgements

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