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Sandstorm erosion testing of anti-reflective glass coatings for solar energy applications

Florian Wiesinger[a,*], Gema San Vicente[b], Aránzazu Fernández-García[c], Florian Sutter[a], Ángel Morales[b], Robert Pitz-Paal[d]

[a] DLR German Aerospace Center, Institute of Solar Research, Plataforma Solar de Almería, Ctra. Senés, km. 4, P.O. Box 39, 04200 Tabernas, Almería, Spain
[b] CIEMAT-Plataforma Solar de Almería, Avd. Complutense 40, 28040 Madrid, Spain
[c] CIEMAT-Plataforma Solar de Almería, Ctra. Senés, km.4, P.O. Box 22, 04200 Tabernas, Almería, Spain
[d] DLR German Aerospace Center, Institute of Solar Research, Linder Höhe, 51147 Cologne, Germany

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ABSTRACT

Components for concentrating solar power applications can suffer from optical performance loss due to their permanent exposure to the environment. There is still lack of experience regarding the destructive effects of sand- and duststorms on glass envelope materials for receiver tubes of parabolic-trough collectors for concentrating solar power (CSP) plants. So far no accelerated aging guideline is formulated yet to account for the performance loss of optical components due to particle erosion to a realistic extent. Within this study 4 different anti-reflective (AR) coatings deposited on borosilicate glass are subjected to an artificial sandstorm test and their resistance towards erosion is evaluated. An uncoated borosilicate glass is also tested as reference. Noticeable differences were obtained depending on the type of coating. Microscope analysis and light transmission measurements in the spectrophotometer were undertaken and it could be concluded that the selection of an AR coating should not only be based on the initial optical performance but also in accordance with meteorological data, especially when erosive sandstorms are expected for the chosen site of the CSP plant.

1. Introduction

In order to perform a reasonable yield analysis for concentrating solar power (CSP) plants, it is of crucial importance to determine all the relevant parameters that are affecting the electrical energy output. Energy conversion processes are limited in their efficiency due to several constraints. Losses can be of optical nature, because of heat losses or further effects like operation strategy or parasitic energy [2]. It is important to note, that all those variables can change over time and thereby have a significant impact on the annual electricity yield of a CSP plant. Performance forecasts over the complete component lifetime are necessary in order to assess the economic benefit of the system as a whole. Typically, the components that are going to be used for CSP installations are subjected to accelerated aging tests which are especially tailored to meet the conditions to be expected during their lifetime [3,4]. Many of those testing procedures are already formulated as standards, like the salt spray test according to ISO 9227 standard [5] for marine environments, the ISO 11507 standard [6] for long-term UV-radiation and cyclic condensation or the IEC 61215 standard test 10.11 [7] for the simulation of thermal cycles. There is no standard available yet to conduct a reasonable testing to simulate erosion effects on optical components for CSP applications caused by sand- and duststorms (SDS). However, some institutes provide fundamental experimental results in this topic. It should be pointed at the work by Sansom et al. [8], who investigated the erosion behavior of different sand types at changing impact velocities for silverd- glass reflector samples. Also, the group around Karim [9] experimentally determined the influence of most of the important parameters like the impact velocity, the impact angle and the sand particle properties on the erosion intensity for solar glass mirrors. An earlier study of the current group compared artificial aging results with naturally eroded reflector samples, that were exposed in the field [10]. Furthermore worth to be mentioned are the works by Houmy et al. [11] and Mahdaoui et al. [12]. All the fore-cited research dealt with erosion on glass- or aluminum reflectors but no study is known that has a closer look on the effects of SDS on the anti-reflective (AR) coatings of glass envelope tubes which present an essential part for parabolic trough solar collectors, though [13].

The AR coating applied to the glass cover is sensitive towards mechanical wear. The low refractive index condition which has to be satisfied by the AR coating to obtain the maximum light transmission on

* Corresponding author.
E-mail address: florian.wiesinger@dlr.de (F. Wiesinger).

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Nomenclature

Symbol

Description, Unit

A	sample area, cm^2
c	volumetric mass concentration, $mg\,m^{-3}$
m	impacting sand mass, g
Sq	root mean square height of surface, µm
t	testing time, s
v	wind velocity, $m\,s^{-1}$
γ	cumulated sand mass per area, $g\,cm^{-2}$
Θ_i	radiation incidence angle, °
λ	wavelength, nm
τ	transmittance,%
$\tau_{s,h}$	solar weighted hemispherical transmittance at λ= [280,2500] nm and Θ_i = 8°, %Subscript

Description

h	subscript indicating hemispherical value
s	subscript indicating solar weighted value after [1]Acronyms

Description

AR	Anti-reflective
CSP	Concentrating Solar Power
MTES	Methyltriethoxysilane
TEOS	Tetraethylorthosilicate
SDS	Sand- and Duststorm
SEM	Scanning Electron Microscope
SSC	Sand- and Duststorm Chamber
US	Ultra Sonic

glass, makes it necessary to use a highly porous material (SiO_2) [14]. The mechanical resistance of this porous coating is considerably lower than the same material dense coating as the pores are filled with air and the bonds between substrate and coating and among the silica material in the coating are weaker. Thus, it is reasonable to assume that damages on the coating might be more intensive than on the uncoated glass. Therefore, special care must be taken for the realistic selection of artificial testing conditions.

The sol-gel dip-coating technology is the most used method for producing AR layers on large glass areas. This process has the ability to coat both sides on the substrate simultaneously and it is the state of the art method to coat the solar glass envelope tubes for parabolic-trough collectors (PTC) at both sides. The porous structure of the film can be achieved by using a colloidal solution [15] or by adding a "porogen" material to the polymeric sol-gel solution [16]. This compound is removed during the heat treatment, generating pores inside the polymeric silica films.

In this paper, different AR coatings prepared by using polymeric solutions are tested in a sandstorm chamber in order to study the resistance under extreme desertic conditions.

2. Methodology

In this section the preparation of the AR coated samples is described as well as the used instruments to characterize them during testing. Furthermore the artificial erosion procedure is explained.

2.1. Sample preparation

In this work borosilicate flat glass substrates with different AR coatings were investigated. Before coating, the 4 mm thick glass samples (dimensions: 7 × 4 cm^2) were cleaned with soaped water and rinsed with distilled water. The polymeric solution was prepared by mixing tetraethylorthosilicate (TEOS), methyltriethoxysilane (MTES), water and ethanol using a molar ratio for alkoxide: water:ethanol of 1: 5: 48, respectively. Hydrochloric acid was used as a catalyst and Triton X-100 as pore generator. The solutions were applied on the substrate on both sides by dip coating. The withdrawal rate was 20 cm min^{-1} and afterwards the samples were introduced in the oven for being heat treated at 500 °C for 15 min. Three different solutions were prepared varying the concentration of Triton X-100 (porogen material). One of them with complete absence of Triton X-100, another with a concentration of 10 g l^{-1}, and the last one with 15 g l^{-1}. Finally, some samples prepared with 15 g l^{-1} were additionally treated with an hydrophobic commercial solution. Sample B5 corresponds to a borosilicate glass with neither coating nor treatment. Table 1 makes clear the nomenclature of the prepared samples.

2.2. Sample characterization methods

The samples were characterized before and after each testing by optical transmittance measurements and optical microscopy. The hemispherical transmittance, $\tau_{s,h}$([280, 2500] nm, 8°, h) was measured with a spectrophotometer model Lambda 1050 from Perkin Elmer which is a state of the art instruments for the characterization of optical solar components [17]. In the nomenclature used, the first parameter in brackets is the wavelength range λ, the second one is the incidence angle Θ_i, and in the third one the index h denotes, that a hemispherical value is given. By application of the ASTM E903 the solar-weighted transmittance $\tau_{s,h}$ can be calculated [18] by averaging the transmittance data over the direct AM1.5 solar spectral irradiance according to ASTM G173-03 [1]. Measurements were performed on three zones of the respective sample and an average value was taken for further evaluation. Before the transmittance measurement was performed, the sample was rinsed with ethanol and immediately dry-blown with pressurized air. The optical inspection was performed with an Axio CSM 700 microscope by Zeiss. The root mean square height Sq of the surface could also be measured in the confocal mode of the microscope. Furthermore a scanning electron microscope of the type S-3400N from Hitachi was used.

2.3. Details on the sandstorm chamber (SSC)

The erosion setup employed in the experiments was a closed loop wind tunnel with particle injection. Fig. 1 shows photographs of the SSC and its sample compartment. The original prototype was a ST200 from the company ITS. It has been equipped with an ultrasonic wind sensor, type FT702LT/D from FT Technologies LTD to monitor the wind velocity inside the SSC. As test dust, Arizona quartz dust from KSL

Table 1
Nomenclature and preparation procedures of the used sample material.

Sample ID	Preparation steps
AR1	No Triton X-100
AR2	10 g l^{-1} Triton X-100
AR3	15 g l^{-1} Triton X-100
AR4	15 g l^{-1} Triton X-100 + hydrophobic treatment
B5	Uncoated borosilicate glass