OPTICAL CHARACTERISATION OF REFLECTOR MATERIAL FOR CONCENTRATING SOLAR POWER TECHNOLOGY

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Abstract

In order to evaluate the quality and suitability of reflector materials for concentrating solar power (CSP) applications a measuring procedure has been developed for the determination of optical key values. These were defined for their relevance in CSP as the solar weighted hemispherical reflectance ρ_{SWH}, the solar weighted direct reflectance ρ_{SWD} within an acceptance angle of interest (25 mrad) and the specular beam diversion σ_{spec}. After measuring those parameters also on artificially degraded samples, an extensive analysis of the optical material properties and comparative lifetime estimation are provided with the intention to lead to a standardized test method. Evaluation of various reflector material samples demonstrates the superiority of glass mirrors over alternative materials (polymer film, aluminium) in all concerned respects with hemispherical and direct reflectances of almost 0.94 and minimal losses after degradation. The high relevance of spectral properties as well as high mechanical resistance is emphasized.

Keywords: solar mirror qualification, optical measurement procedure, specular reflectance, hemispherical reflectance, specular beam diversion

1. Introduction

Along with the market for concentrating solar power technology the industry that provides components for solar power plants is growing. New materials and manufacturing procedures are being introduced. The collecting mirror constitutes a key component that has potential for further development, but also has to meet high quality requirements. Apart from the construction accuracy of the reflector shape, the reflective material itself must feature high specular reflection of the solar irradiance and consistency of its reflective properties under long lasting environmental influence, while manufacturing costs need to be low. Because of missing technical guidelines, various parameters have been reported in the past for solar mirrors, with some of them giving misleading results. There is a need for standardized key figures and measurement procedures that give suppliers and customers of solar power technology access to proper information regarding the mirror-material quality.

The topic has been addressed in recent work in the *DLR QUARZ Test and Qualification Center for CSP Technologies* and in this paper a procedure is presented that was developed on the basis of existing European and international standards. From the methods, instruments and proceedings recommended in standards like DIN 5030[1] and DIN 5036[2] about optical material properties in general and those that deal with measurement techniques of hemispherical and specular reflection on mirrors or glossy materials and coatings like ASTM E 903[3], DIN EN 12373-11[4], DIN EN 12373-12[5] and DIN 67530[6], the appropriate ones were selected and combined specifically for their relevance to characterize concentrating solar mirror materials.

2. Key figures and associated measurement methods

2.1. General parameter specifications

In solar applications the aim is to concentrate more than 90% of the incident sunlight onto the absorber, which requires the mirror to have very high specular reflection properties of the solar spectrum. This is achieved by using a highly reflective material like silver or aluminium and by a very smooth mirror surface. Because of actual solar collector geometries, the absorber acceptance function allows tolerances for reflector errors (including reflector shape, tracking, sunshape etc.) that can lead to an offset to the ideally onto the absorber projected sunbeam, of up to 20 mrad to either side. For the parameter of mirror reflectance regarded in this paper, it is therefore expected that all within 25 mrad (full-angle) reflected sunlight is concentrated onto the absorber.

The proposed nomenclature and definitions for reflectivity characterisation is illustrated in figure 1. According to physical law, the two extreme cases of reflection are the diffuse scattering reflection in the whole hemisphere and the perfect specular reflection described by the law of reflection (incidence angle equals emergent angle). The associated reflectance values are named hemispherical reflectance ρ_{hem} and specular reflectance ρ_{spec}. The surface smoothness of a reflective material is essential for the characteristic of these parameters. A perfectly smooth mirror will collect all reflected light inside ρ_{spec} which therefore shows the same value as ρ_{hem} and produces a gloss of 1, when gloss is defined as the ratio of ρ_{spec} to ρ_{hem}.

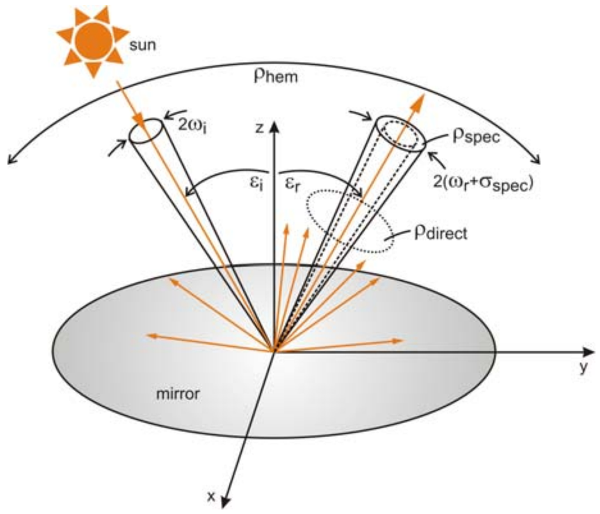

Figure 1: Schematic of reflection

A slightly irregular surface quality results in a broadening of the specular reflected beam profile by an angle defined as σ_{spec} (offset half angle of one standard deviation to the line of perfect specular reflection). Also, microstructures in the surface can lead to an additional diffuse scattering. All light collected inside an aperture with a selected acceptance angle (e.g. 25 mrad) set around the area of ρ_{spec} is defined as the direct reflectance ρ_{direct}. In CSP applications the parameter values need to be weighted with the solar irradiance spectrum and result in the solar weighted hemispherical reflectance ρ_{SWH} and the solar weighted direct reflectance ρ_{SWD}. The latter is the most relevant value because it describes the amount of sunlight that can be expected to hit the absorber. In the following the procedure for measuring these key figures is described.

2.2. Spectral hemispherical reflectance

The spectral hemispherical reflectance $\rho_{hem}(\lambda)$ is measured in the wavelength range of 250-2500 nm (in 5 nm intervals) with a UV/Vis/NIR grating spectrophotometer (*Perkin-Elmer Lambda 950*) equipped with an integrating sphere of 150 mm diameter. Depending on the sample being a first or second surface mirror, an equal NIST-traceable reference mirror standard is used. The acquired reflectance spectrum is then weighted with the typical direct solar irradiance spectrum for European and North-American latitude (AM 1.5) provided by the active standard ASTM G173[7]. The result is the *solar weighted hemispherical reflectance* ρ_{SWH}.

2.3. Direct reflectance

With a reflectometer using a similar principle as described in DIN 67530[6] (*Devices & Services 15R portable reflectometer)* the direct reflectance $\rho_{direct}(\lambda=660nm)$ is measured at 660 nm wavelength and near normal incidence angle (8°). In the instrument a collimated light beam is reflected by the sample and passes an aperture that restricts the diameter of the beam-cone that reaches the detector and allows 25 mrad full angle of acceptance. Validation measurements with a specular accessory of the *Lambda 950* spectrometer (where the acceptance angle is unknown) showed the gloss of a mirror to be approximately constant (within 1.6 – 3 percentage points deviation) over the concerned wavelength spectrum of 250-2500 nm. Therefore it is assumed that the ratio of direct reflectance to hemispherical reflectance over the entire spectrum is constant as well as the ratio at one wavelength interval. From the direct measurement at 660 nm wavelength the *solar weighted direct reflectance* ρ_{SWD} is calculated with:

$$\rho_{SWD} = \frac{\rho_{direct}(\lambda = 660nm)}{\rho_{hem}(\lambda = 660nm)} \cdot \rho_{SWH}$$

2.4. Specular beam diversion

To determine the broadening of the specular reflected beam on real mirror surfaces a setup with a high dynamic range camera (*Charm*) was built. A point light source is used as an object that is imaged by the camera creating an image with the size of approximately one pixel on the CCD. A perfect mirror placed in the optical path does not interfere in the imaging process, whereas the image size on the chip increases after reflection on a mirror with a surface that broadens the specularly reflected beam cone. The design relates the angle of beam diversion to the image enlargement by 0.13 mrad per pixel. Assuming a bi-variate Gaussian intensity distribution, the center of mass is found and the standard deviation is calculated on the long main axis of a fitted ellipse. From the standard deviation in pixels the angle of specular beam diversion σ_{spec} is determined in mrad.

2.5. Mechanical durability

As indicator for mechanical stability of a mirror a new method has been established to simulate aging by abrasion due to cleaning processes and sand or dirt in the air. An abrasion instrument (*Taber Linear Abraser Model 364*) is utilized for a test based on ISO 9211-4[8]. The instrument uses a standardized grinding head and moves linearly across the sample with specified abrasion parameters for speed, pressure and pathlength. The sample is subjected to 10 to 10000 cycles of grinding (in intervals of a factor 10) and the degradation is evaluated by direct and hemispherical reflectance measurements of the so treated areas. The *reduced direct reflectance* ζ_{direct} is introduced as a fraction of the original reflectance, where *n* is the number of grinding-cycles:

$$\zeta_{direct}(n) = \frac{\rho_{direct}(n)}{\rho_{direct}(n=0)}$$

The *reduced hemispherical reflectance* ζ_{hem} is defined accordingly.

3. Results

3.1. Overview of tested materials and results

In the process of determining and verifying the procedure many mirror samples proposed for CSP were measured. In this paper the results of four samples are presented as a representation of the currently main development directions for reflector material. Two samples are based on aluminium, one is a polymer film mirror and one a second surface glass mirror. All were subjected to a full optical analysis according to the procedures described in chapter 2. An overview of the resulting values of the measurements is given in table 1, while the full data are presented in the following subchapters.

Reflectance	Glass mirror	Polymer film	Aluminium 1	Aluminium 2
ρ_{SWH} ASTM G173	0.939	0.922	0.903	0.868
ρ_{SWD} ASTM G173	0.939	0.874	0.830	0.835
Gloss	1.00	0.95	0.92	0.96
ζ_{hem} (100 cycles)	1.00*	0.96	1.00	0.98
ζ_{direct} (100 cycles)	0.99	0.27	0.92	0.67
σ_{spec} [mrad]	<< 0.3†	0.9	1.2	0.8

Table 1: Reflectance values of different mirrors for application in CSP

3.2. Reflectivity measurements

In figure 2 the hemispherical reflectance spectra of the tested mirror samples are shown together with the relative solar irradiance spectrum. Because of the distribution of the solar spectrum, the strongest interest lies in the visual wavelength region. Spectral differences of mirror reflectance in this region have a high influence on the solar weighted reflectance value. The graphs also reveal variation between the aluminium materials.

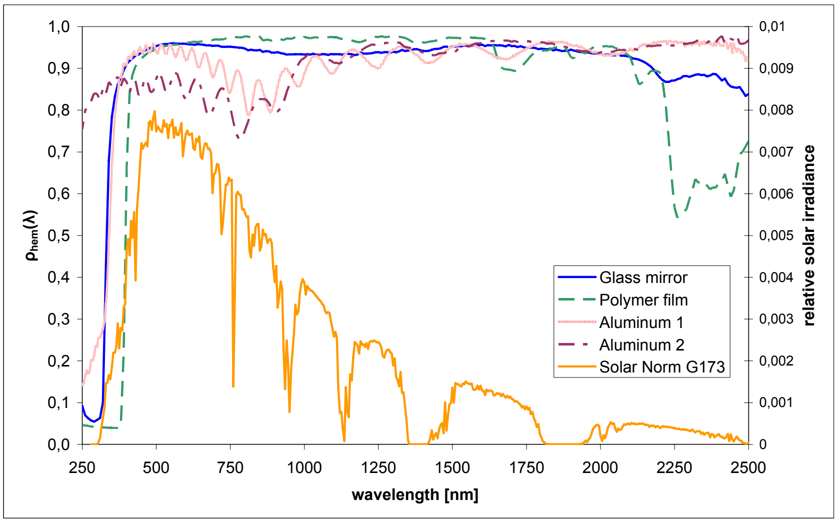

Figure 2: Hemispherical reflectance spectra of different material samples

3.3. Abrasion testing

The abrasion testing effectively shows significant differences in the mirror surface stability, as presented in table 1 of the reduced reflectances and in figure 3, where the hemispherical and direct reduced reflectances are plotted versus the number of grinding cycles. The essential result of this test is the strong effect that the degradation of mirror surface has on the direct reflection, while the hemispherical reflection is hardly affected until severe damage.

* measurement was run on different but comparable mirror than top values (same for ζ_{direct})
† resolution limit of instrument

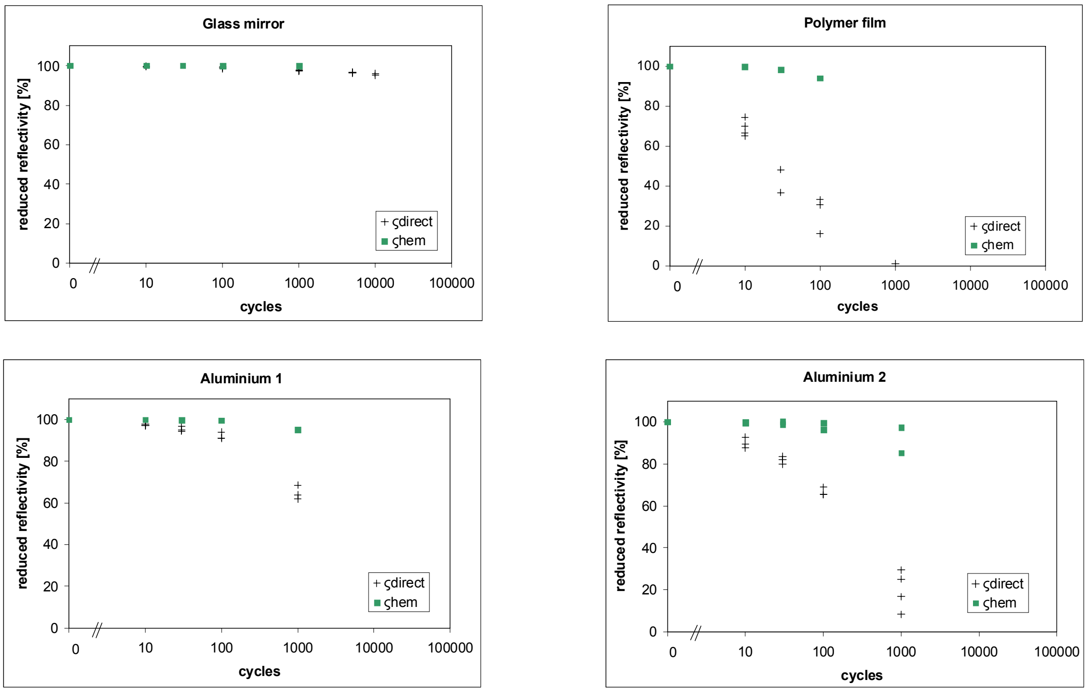

Figure 3: Abrasion results of different material samples

3.4. Specular beam diversion

In figure 4 the images of the specular beam distribution as recorded by *Charm* are displayed. The specular beam diversion σ_{spec} calculated from the images is listed for each sample in table 1. The images show the complete specular beam profile (3-4 standard deviations respectively σ_{spec} in both directions to zero) and demonstrate the marginal size of specular beam diversion for all samples. Anisotropic microstructures in the mirror surface produce ellipsoid distributions.

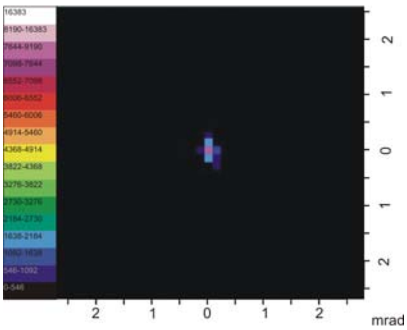

Figure 4a: Glass mirror

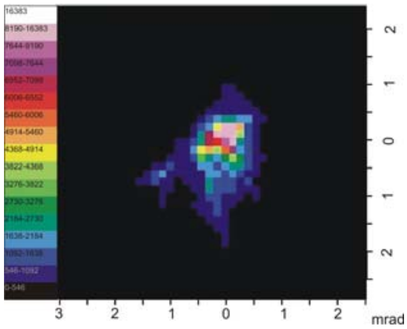

Figure 4b: Polymer film

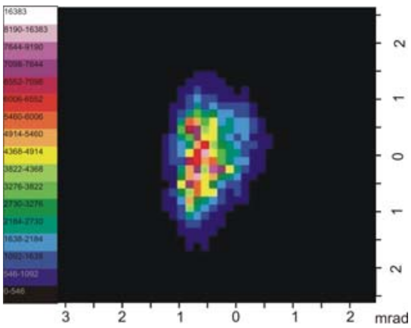

Figure 4c: Aluminum 1

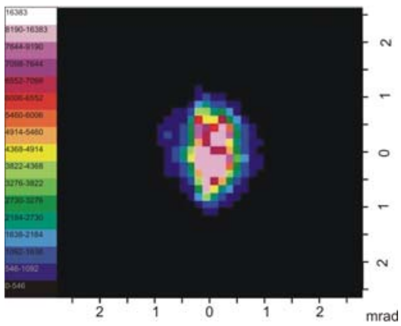

Figure 4d: Aluminum 2

Figure 4: Images of specular beam diversion of different material samples

4. Discussion

The reflection analysis confirms the superiority of silvered glass mirrors used traditionally in concentrating solar collectors. High performance of these materials is achieved by the high hemispherical and direct reflectance of almost 0.94. This is due to their high surface quality which prevents scattering and beam diversion (below measurement sensitivity) as can be seen in figure 4a. Polymer film with a silvered reflective layer also reaches reflectance values above 0.9, but only hemispherically. The surface smoothness does not reach glass quality and therefore gloss and direct reflectance values are by about 5 percentage points lower than hemispherical values. Still the reflectivity properties of Polymer film outperform the aluminium materials, whose hemispherical values lie between 0.903 and 0.868. Because of better surface quality which results in reduced losses of only 3.3 percentage points in comparison to more than 7, the inferior hemispherical values of Aluminium 2 level with Aluminium 1 in the direct reflectance. The beam diversion of all glass alternatives are similar and lie between σ_{spec} = 0.8 and σ_{spec} = 1.2, which is well within the required boundary values of 3-4 mrad.

Glass mirrors are superior in their surface durability as well. Even after a considerable amount of grinding during the abrasion test the optical properties are only marginally affected, which can be attributed to the surface robustness of the glass. The other materials being first surface mirrors are much more sensitive to surface degradation, especially the Polymer film. This leads to very limited lifetime estimation. Materials as sensitive as the Polymer film are assumed to suffer deterioration of their reflective properties in daily usage quickly and the necessity to replace such mirrors after a short period of time can be assumed. Because the degradation most significantly affects the specular and direct reflection properties in comparison to the hemispherical ones, it is important to consider the direct reflectance when qualifying collector mirrors that have been in use for several years.

5. Conclusion

On the basis of existing measurement methods a measurement and evaluation procedure of reflective materials for applications in concentrating solar power technology has been established and the key values of solar weighted hemispherical reflectance ρ_{SWH}, the solar weighted direct reflectance ρ_{SWD} and the angle of beam diversion ρ_{spec} have been defined. The test results of different reflector material samples demonstrate that the evaluation of mirror quality and its ranking is dependent on the considered key parameters. For actual requirements in CSP the value of the solar weighted direct reflectance ρ_{SWD} at 25 mrad (1.4°) acceptance angle represents the most significant value for suitability evaluations. A new approach has been introduced for mechanical durability tests on the mirror surface to simulate abrasive aging. It is considered a procedure that delivers reproducible values at reasonable time and effort and visualizes differences in the material stability as demonstrated in the results. A relation to actual environmental conditions cannot be given at this stage but the test helps to estimate if a material can be expected to maintain the measured reflective properties in longterm use.

Measurement experience and the presented results of different example materials prove the superior quality of glass mirrors as reflector material. Other materials using silver as reflective layer also exhibit high solar weighted hemispherical reflectance values. But they show significant reductions (more than 3 percentage points) in the direct reflectance due to lower surface quality and mechanical stability. Further development is needed to enable alternative reflector materials to reach glass quality.

All key parameters combined improve the knowledge about the optical material properties and make the presented analysis procedure a powerful tool to assess the properties in the development process, for investment decisions and for comparison of different mirror materials.

Acknowledgements

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References

[1] DIN 5030, Optical radiation physics and illumination engineering; quantities, symbols and units (1982)

[2] DIN 5036, Radiometric and photometric properties of materials (1980)

[3] ASTM E 903-82 (reapproved 1992), Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres (1992)

[4] DIN EN 12373-11, Aluminium and aluminium alloys – Anodizing – Part 11: Measurement of specular reflectance and specular gloss of anodic oxidation coatings at angles of 20°, 45°, 60° or 85° (2000)

[5] DIN EN 12373-12, Aluminium and aluminium alloys – Anodizing – Part 12: Measurement of reflectance characteristics of aluminium surfaces using integrating-sphere instruments (2000)

[6] DIN 67530, Reflectometer as a means for gloss assessment of plane surfaces of paint coatings and plastics (1982)

[7] ASTM G173-03, Terrestrial Reference Spectra for Photovoltaic Performance Evaluation (2003).

[8] DIN ISO 9211-4, Optics and Optical Instruments – Optical Coatings – Part 4: Specific test methods, (2006).