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Optical properties, durability, and system aspects of a new aluminium-polymer-laminated steel reflector for solar concentrators

Maria Brogren[a,*], Anna Helgesson[b], Björn Karlsson[b,c], Johan Nilsson[c], Arne Roos[a]

[a] *Division of Solid State Physics, Department of Engineering Sciences, Uppsala University, Box 534, Uppsala 751 21, Sweden*

[b] *Vattenfall Utveckling AB, Älvkarleby 814 26, Sweden*

[c] *Division of Energy and Building Design, Department of Construction and Architecture, Lund University, P.O. Box 118, Lund 221 00, Sweden*

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Abstract

A newly developed aluminium-polymer-laminated steel reflector for use in solar concentrators was evaluated with respect to its optical properties, durability, and reflector performance in solar thermal and photovoltaic systems. The optical properties of the reflector material were investigated using spectrophotometer and scatterometry. The durability of the reflector was tested in a climatic test chamber as well as outdoors in Älvkarleby (60.5°N, 17.4°E), Sweden. Before ageing, the solar weighted total and specular reflectance values were 82% and 77%, respectively, and the reflector scattered light isotropically. After 1 year's outdoor exposure, the total and specular solar reflectance had decreased by less than 1%. However, after 2000 h in damp heat and 1000 W/m^2 simulated solar radiation, the optical properties had changed significantly: The light scattering was anisotropic and the total and specular solar reflectance values had decreased to 75% and 42%, respectively. The decrease was found to be due to degradation of the protective polyethylene terephthalate (PET) layer, caused by UV radiation and high temperature. The conclusions are that the degradation is climate dependent and that PET is not suitable as a protective coating under extreme conditions, such as those in the climatic test chamber. However, the results from

*Corresponding author. Angstrom Laboratory, Department of Engineering Sciences, Uppsala University, P.O. Box 534, Uppsala S-75121, Sweden. Tel.: +46-18-471-31-31; fax: +46-18-500-131.

E-mail address: maria.brogren@angstrom.uu.se (M. Brogren).

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outdoor testing indicate that the material withstands exposure in a normal Swedish climate.

Keywords: Solar concentrators; Reflector materials; Optical properties; Accelerated ageing; Durability

1. Introduction

1.1. Concentrating solar energy systems

Due to the relatively high material and production costs of solar cells and solar thermal absorbers, it is desirable to find alternative ways of reducing the cost of photovoltaic electricity and solar heat. One approach is to use concentrators that increase the irradiance on the modules or absorbers and thus the electricity or heat production per unit receiver area, which in turn reduces the area needed for a given output. Concentrating systems use lenses or reflectors to focus sunlight onto the solar cells or solar thermal absorbers. High concentration of solar radiation requires tracking of the sun around one axis or two axes, depending on the geometry of the system. The higher the concentration, the more concentrator material per unit area of solar cell or thermal absorber area is generally needed. It is therefore more appropriate to use lenses than reflectors in highly concentrating systems, because of their lower weight and material costs. Lenses, typically point-focus or linear-focus Fresnel lenses with concentration ratios of 10–500×, are most often manufactured out of inexpensive plastic material with refracting features that direct light onto a small or narrow area of photovoltaic cells or on a linear thermal absorber. The cells are usually silicon cells. Single- or mono-crystalline silicon approaches accounted for 93% of the annual cell production in 2002 [1]. Cells of GaAs and other compound materials have higher conversion efficiencies than silicon, and can operate at higher temperatures, but they are often substantially more expensive [2]. Concentrator module efficiencies range from 17% and upwards and concentrator cells have been designed with conversion efficiencies in excess of 30% [3,4]. Concentrator systems that utilize lenses are unable to focus scattered light, limiting their use to areas with mostly clear weather.

In areas with a lot of diffuse irradiation, as well as for moderate (5–20×) and low (<5×) concentration ratios, reflectors are often more cost-effective than lenses and therefore the most common type of concentrator. Below 5× concentration, it is possible to construct cost-effective static concentrators, both for photovoltaic and solar thermal systems [5,6]. These are mostly two-dimensional parabolic troughs or plane booster reflectors. Plane mirrors in front of the collector area increase the collected energy with 20–50% and reduce some of the diurnal variation [7].

1.2. Solar reflector materials

Reflectors for solar energy applications should fulfil a number of requirements

- They should reflect as much as possible of the useful incident solar radiation onto the solar thermal absorbers or the photovoltaic cells.

- The reflector material and its support structure should be inexpensive compared to the solar cells or thermal absorbers onto which the reflector concentrates radiation.
- The high reflectance should be maintained during the entire lifetime of the solar collector or photovoltaic module, which is often longer than 20 years.
- If cleaning is necessary, the surface should be easily cleaned without damaging its optical properties and the maintenance should not be expensive.
- The construction must be mechanically strong to resist hard winds, snow loads, vibrations, etc.
- The reflector should preferably be lightweight and easy to mount.
- The reflector material should be environmentally benign and should not contain any hazardous compounds.
- The visual appearance of the reflector should be aesthetical, since solar concentrators often are large and must be placed fully visible on open spaces so that the concentrator aperture is not shaded by objects in the surroundings.

The optical requirement that must be fulfilled for reflector materials in solar thermal applications is a high reflectance in the entire wavelength range of the solar spectrum (300–2500 nm). In photovoltaic applications, photons with lower energy than the band gap of the solar cell, which corresponds to wavelengths longer than about 1100 nm for a silicon cell, do not contribute to the photoelectric conversion but only to overheating. High cell temperatures reduce the output voltage and a high reflectance in the infrared is therefore counterproductive in photovoltaic applications. Hence, metals that are free electron-like and obey the Drude model [8] are suitable as reflectors for solar thermal applications, but not optimal for photovoltaics. There are no known metals that combine a low reflectance in the near-infrared with a high reflectance in the ultraviolet and in the visible. However, such a selective reflectance can be obtained by an application of thin films on top of the reflecting metal, which are absorbing in the near-infrared, for example doped tin oxide [9].

Among the Drude metals, silver and aluminium are the best solar reflectors [10], with a solar hemispherical reflectance of approximately 97% and 92%, respectively. Due to its lower cost, the material which is most often used for solar reflectors today is anodised aluminium. However, if the anodised aluminium is not protected, for example by a glazing, a plastic foil, or a lacquer, its optical performance degrades severely in only a couple of months [11]. The degradation of silver is essentially as rapid as that of aluminium [12]. Due to the limited corrosion resistance of the free electron-like metals, they are often used in back surface mirrors, evaporated on the back of a glass or polymer substrate that protects the metal from oxidation. Among the state-of-the art in solar reflector materials are back-surface-silvered low-iron glass or polymethylmethacrylate (PMMA) [13]. However, glass mirrors tend to be brittle and heavy. Front surface mirrors, on the other hand, are often bendable and of light weight, but more susceptible to chemical attack [14].

A solar reflector is not subject to the same high temperatures and thermal cycling as a solar absorber. Nevertheless, environmental conditions impose stringent demands on the material, whose surface will deteriorate more or less upon exposure to the environment. Loss of solar reflectivity can result from erosion or oxidation of the surface, dirt accumulation on the reflector, and action of cleaning agents [15]. While degradation caused by accumulation of dust on the reflecting surface is essentially reversible, surface oxidation is not [16].

The optical performance of solar reflectors thus depends on the mechanical and chemical properties of the surface and the protective coating, if such is present. For flexible reflective foils, a support of sheet metal may be necessary, while only a simple frame construction is needed if the reflector is self-supporting, which is the case for corrugated sheets. When installing booster reflectors, the cost of the reflector material, the frame and support construction, as well as mounting and installation of the reflector must be taken into account. Maintenance should also be included in life-cycle cost.

1.3. Swedish experiences with booster reflectors

Since the beginning of the 1980s, several large ground-based solar thermal collector systems have been installed in Sweden. These collectors show the lowest costs of solar energy systems in Sweden. During the 1990s, a number of solar energy systems in Sweden and Denmark have been equipped with external, trapezoidal corrugated booster reflectors of aluminium. One example is the installation in1994 of a collector field at Östhammar (60.2°N, 18.2°E) in Sweden. In the Östhammar system, the reflectors are made of a corrugated lacquered aluminium sheet with an initial solar reflectance of about 63%. The use of reflectors increases the annual heat production from 380 to 490 kWh/m^2, an increase of almost 30% [17]. The solar reflectance of the booster reflectors in the Östhammar system is low, partly due to the thick layer of poly(vinylidene fluoride)-based lacquer (PVF2). If the booster reflectors in the Östhammar solar collector field had been made of highly reflective anodised aluminium with a solar reflectance of 85%, the annual output could have been as high as 530 kWh thermal energy per m^2 collector area, or 40% higher than without reflectors. However, the durability of the lacquered reflector has shown to be good, while the optical properties of anodised aluminium reflectors often have degraded severely after 10 years outdoor exposure.

1.4. Reflector laminates

Aluminium is often used as a reflector material, for internal as well as external reflectors, in solar energy systems. In order to be self-supporting in the latter case, the aluminium sheet must often be thicker than 4 mm. Stainless steel, on the other hand, is rigid and does not have to be as thick as an aluminium sheet. Austenitic steel has a long-term stable but rather low solar reflectance (67%) [14].

One way for cost-minimization of concentrators, which is proposed in this article, is to laminate a thin aluminium foil on a steel substrate, thus obtaining the good mechanical properties of steel, the high solar reflectance of aluminium, and the degradation protection of the plastic laminate. In this way, the reflector performance can be improved without significantly increasing the material cost.

The technique of combining different materials by lamination is not new. For example, thin, flexible metal-polymer laminates can be purchased on rolls. Traditionally, these laminates are used within the packaging industry, but there are other applications as well. The combination of materials with different properties makes it possible to tailor the properties of the product for different applications. As stated above, a solar reflector material should have high reflectance, long durability, mechanical strength, and low cost. Since high reflectance is a property that is determined by the surface of the material, it can be created using thin films (for example of aluminium). The substrate is then chosen to fulfil specific requirements on mechanical properties and a protective coating is used to prevent degradation of the reflective layer. The lamination process will differ with the choice of materials in the laminate. If the substrate is a rigid steel sheet, it may be impossible too to use a roll process, and if the protective coating is a lacquer, spray painting may be utilized instead of lamination of the top layer.

1.5. Objective of this work

The overall objective of an ongoing Swedish project is to increase the performance of low-concentrating solar energy systems with reflectors, without increasing system cost [18]. The approach is to design and manufacture new reflector materials that combine the mechanical properties of steel sheet with the high solar reflectance of aluminium. Consequently, a reflector laminate consisting of a polymer coated highly reflective aluminium foil on a rigid steel sheet has been produced and reflectors have been manufactured of this material. The reflectors are primarily intended for large ground-based collector fields in which its use is expected to increase the annual thermal output by 40% compared to the yield without reflectors.

In the work that is presented in this article, the optical properties and degradation of the new reflector material have been evaluated.

2. The new reflector material

2.1. Design and manufacturing of a laminated Al-on-steel reflector

Because of its rigidity, a steel sheet with a thickness of 0.50 mm was chosen as substrate for the new reflector laminate. A 4 μm layer of polyurethane glue was applied on the steel sheet and it was hot pressed together with a reflective laminate which is a sandwich of 25 μm polyethylene terephthalate (PET)/20 nm evaporated aluminium/9 μm rolled aluminium foil/20 μm PET. The thicker PET is the top layer. The final product thus consists of the following layers:

- Protective layer of 25 μm clear, UV stabilised PET, which has a high-solar transmittance (see Section 5), high melting point (255°C) and good stability in ultraviolet radiation. However, according to the product specifications, PET is not long-term stable at higher temperatures than 110°C.

- Reflective layer of aluminium, evaporated directly on the back of the protective film. Evaporated aluminium gives a high solar reflectance with a low diffuse component. However, the surface must be protected from exposure to humidity, high temperature, and air pollutants in order to keep its optical properties long-term stable.
- Substrate, which is a laminate of 9 μm aluminium (which protects the evaporated aluminium from moisture and provides a fairly good "back up reflectance" if the evaporated aluminium would be damaged) and 20 μm PET that, in turn, is heat laminated on a 0.50 mm steel sheet. Mechanical testing, performed by the manufacturer, showed that the steel sheet is mechanically strong and has a stiffness constant, $k > 10\,000$ N/m, which makes the reflector self-supporting.

Fig. 1 shows a schematic of the manufacturing process for the Al-on-steel reflector sandwich. To date, 200 m^2 of the Al-on-steel reflector have been manufactured using this process.

2.2. Construction of a booster reflector of trapezoidal corrugated Al-on-steel for a solar collector

Part of the produced reflector sheet has been trapezoidal corrugated and a large booster reflector has been constructed from the corrugated sheet and installed in front of a conventional flat plate solar collector in Älvkarleby (60.5°N, 17.4°E), Sweden, see Fig. 2. The heat production from the collector with a booster reflector of Al-on-steel is continuously monitored and compared to the output of similar collectors without reflectors in order to evaluate the performance of the new reflector material in a solar energy system.

Corrugation makes the metal sheet more rigid and prevents deformation. A trapezoidal corrugation can be obtained by bending or rolling. However, rolling often requires a minimum production volume in order not to result in a too

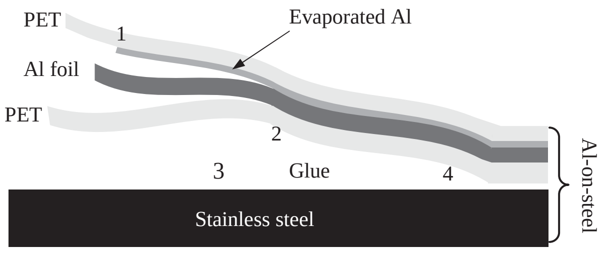

Fig. 1. The manufacturing of the Al-on-steel reflector. A 20 nm layer of aluminium is evaporated on a 25 μm PET foil (1), the PET foil with evaporated aluminium, a 9 μm rolled aluminium foil, and a 20 μm PET foil are laminated together (2), a 4 μm layer of glue is applied on a 0.5 mm thick sheet of stainless steel (3), the PET/Al/Al/PET sandwich and the steel sheet is hot pressed together to form the reflector laminate (4).

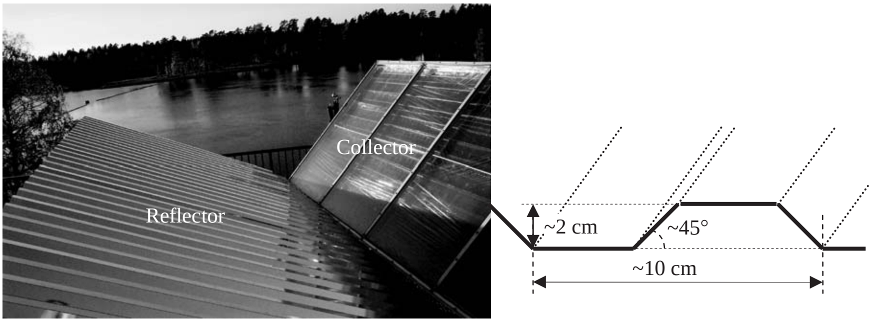

Fig. 2. A 18 m^2 trapezoidal corrugated Al-on-steel booster reflector, mounted in front of a 13 m^2 planar solar collector in Älvkarleby (60.5°N, 17.4°E), Sweden (left) and a schematic picture of the trapezoidal corrugation (right).

expensive product. Thus, for economical reasons, the corrugation of the single reflector was shaped by bending instead of rolling.

The solar collector, which faces south, has an absorber area of 13 m^2 and an inclination of 45°. Both reflector and collector are 6 m wide. The inclination of the 18 m^2 reflector is 25°. There is a 0.2 m gap between the bottom of the collector and the reflector in order to prevent a build-up of snow or leaves in front of the collector.

In the mornings and in the afternoon, when solar radiation hits the reflector at a non-zero azimuth angle, some of the reflected radiation has been found to miss the collector. To avoid these effects, a wider reflector should be used.

2.3. Construction of photovoltaic-thermal MaReCo systems with Al-on-steel reflectors

In addition to the large trapezoidal corrugated reflector in Älvkarleby, the Al-on-steel reflector material will be used in so called MaReCo concentrators [19–22] for a several $kW_{electric}$ photovoltaic-thermal co-generation system in Hammarby sjöstad, a new residential area in Stockholm (59.2°N, 18.3°E), Sweden. In principle, the photovoltaic-thermal MaReCo consists of an asymmetrically truncated compound parabolic concentrator trough using a hybrid absorber, with solar cells laminated on one side of a standard thermal absorber [23], which is placed along the focal line of the concentrator trough. This system also includes a cover glass that prevents convective and radiative thermal losses as well as protects the hybrid absorber and the reflector.

The Hammarby sjöstad system is designed, ordered, and manufactured, and will be delivered and installed during spring 2004.

3. Experimental methods

The Al-on-steel material was exposed to a number of tests, which are summarised in Fig. 3. The methods that were used are described in the following sections and the

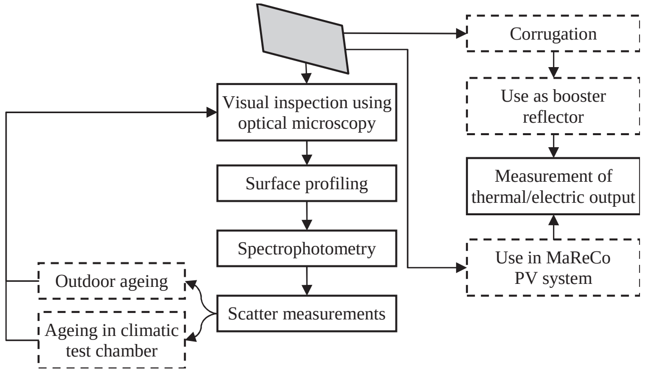

Fig. 3. The methods used for analysis of the Al-on-steel reflector laminate.

results that were obtained are presented in Section 4. The material is also tested according to the agreed upon conditions in the International Energy Agency's Solar Heating and Cooling Programme's Task 27 testing group [24]. These tests are ongoing and the results not yet available.

3.1. Optical microscopy and surface profilometry

The surface of the Al-on-steel reflector was analysed using an Olympus BX 60 optical microscope equipped with a Ikegami ICD-700PAC CCD color camera, which was connected to a computer for image analysis. Photographs of the surface were taken before and after ageing.

The surface profile of the Al-on-steel reflector was measured before and after ageing, using a Veeco Dektak V 200-Si profilometer. The scan length was 5 mm in all scans. The surface roughness (RMS) was calculated from measurement data. The calculation was performed by first fitting a second-order polynomial curve to measurement data, then subtracting this curve from the data in order to account for a bent sample, and finally calculating the standard deviation of the resulting curve.

3.2. Spectrophotometry

The wavelength-dependent diffuse and total reflectance, $R_{\mathrm{diff}}(\lambda)$ and $R_{\mathrm{tot}}(\lambda)$, at near normal angle of incidence were measured using a Lambda-900 spectrophotometer from Perkin-Elmer, equipped with an integrating sphere. The measurements were performed at every fifth nanometre for wavelengths, λ, between 200 and 2550 nm. It was considered sufficient to measure the reflectance in this wavelength interval as it covers more than 98.5% of the total terrestrial solar power [25].

The diffuse reflectance was measured by letting the specularly reflected beam escape through a $3.4 \times 3.4\ \mathrm{cm}^2$ square port in the integrating sphere, while the total reflectance was measured with the port closed. The diameter of the integrating sphere was 15 cm. The large dimensions of the exit port in combination with the relatively small sphere radius results in an angular interval of $\pm 6.5^{\circ}$ within which the scattered radiation that exits the sphere in the corners of the port is defined as "specular". Hence, a significant part of the low-angle scattered radiation may not be included in the radiation that is measured as diffuse. On the other hand, the image of the light source on the sample is oblong, which results in an oval specularly reflected beam, of which the top and bottom parts almost hit the sphere wall instead of escaping through the exit aperture Thus, light that is reflected with an angle of only a fraction of a degree (which we would like to be measured as specularly reflected) may miss the exit aperture and be mistaken for diffuse reflectance. The square shape of the exit aperture in combination with the oblong image of the light source on the sample, thus results in an averaging over the angular interval $-6.5<\theta<6.5^{\circ}$, in which part of the reflected radiation will be measured as diffuse and part will be measured as specular. Hence, the geometry of the instrument makes the measured absolute values of the specular and diffuse reflectance uncertain within a few percent. However, it is possible to make a comparison between the values before and after ageing, provided that the scattering is isotropic. If the scattering is anisotropic, the uncertainty in the measured diffuse reflectance increases [26], and it may be necessary to measure the same sample several times, rotated around its surface normal, and to calculate the mean value of the measured diffuse reflectance values. In this work, the image of the light source on the exit port was inspected before the diffuse reflectance was measured and the sample was rotated around its surface normal as to let a virtual mean value of the "specular" image of the light source escape through the port.

Keeping the complication discussed above in mind, the specular reflectance $R_{\text{spec}}(\lambda)$ was calculated as the difference between the measured $R_{\text{tot}}(\lambda)$ and $R_{\text{diff}}(\lambda)$. The integrated total solar reflectance, $R_{\text{tot}}^{\text{solar}}$, was calculated from measurement data using

$$R_{\text{tot}}^{\text{solar}} = \frac{\int_{305\text{ nm}}^{2537\text{ nm}} R_{\text{tot}}(\lambda) G_{\text{tot}}(\lambda)\,\mathrm{d}\lambda}{\int_{305\text{ nm}}^{2537\text{ nm}} G_{\text{tot}}(\lambda)\,\mathrm{d}\lambda}. \tag{1}$$

In Eq. (1), $G_{\text{tot}}(\lambda)$ denotes the wavelength dependent global solar radiation on a horizontal surface. The international reference solar spectrum for air mass 1.5 [25,27] was used in the calculations. Wherever the wavelength intervals of the measured reflectance spectra did not match the available irradiance data, the measured spectra were interpolated. The diffuse and specular solar weighted reflectance values, $R_{\text{spec}}^{\text{solar}}$ and $R_{\text{diff}}^{\text{solar}}$, were calculated correspondingly.

3.3. Accelerated ageing in a climatic test chamber

A $20 \times 30\ \text{cm}^2$ sample of the laminated Al-on-steel reflector was aged for totally 2000 h in a VCL 4033/MH climatic test chamber from Heraeus-Vötsch. The sample did not have any edge tape or other edge sealing. A five-hour test cycle, see Fig. 4, was repeated 400 times. During half of each cycle a 2 kW metal–halogen lamp was lit that radiated in the wavelength range 280–3000 nm. The spectral distribution of the radiation from the metal-halogen has not been characterised and there is a possibility

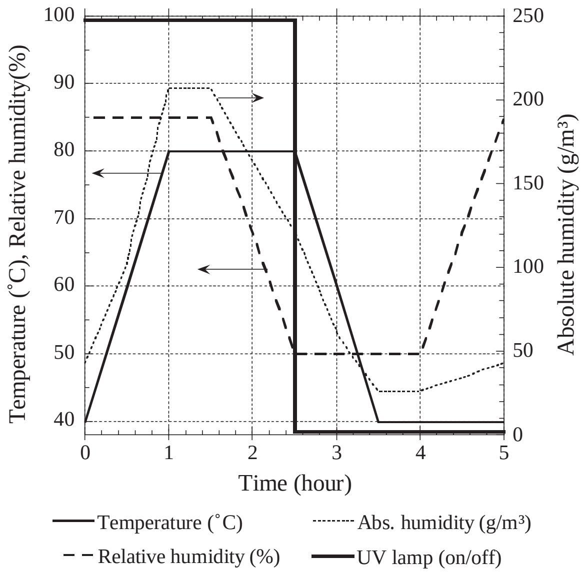

Fig. 4. Test cycle for accelerated ageing, which was repeated 400 times.

that there is disproportionally high ultraviolet irradiance in the test chamber compared to in real sunlight. If this is the case, it may cause unrealistic degradation due to irradiance at wavelengths below the terrestrial cut-off at about 300 nm [28]. The lamp was located in the middle of the ceiling of the chamber, 60 cm from the grid where the sample was placed, and the resulting irradiance on the sample was approximately 1000 W/m^2. In addition to radiation, the programmed test cycle included two different levels of high temperature and two levels of humidity. The relative humidity was set to vary between 50% and 85% and the temperature was set to vary between 40°C and 80°C, resulting in an absolute humidity varying between 25 and 210 g/m^3. The temperatures in the test were significantly lower than the temperatures that are used for temperature testing of solar thermal absorbers [29], since the operating temperatures of a reflector are lower than those of a thermal absorber and the aim was not to impose conditions that are essentially different from real operating conditions on the reflector material, but only to accelerate the degradation process. No air pollutants were injected in the climatic test chamber during the accelerated testing.

3.4. Outdoor exposure

In addition to accelerated ageing, the reflector material was exposed outdoors in Älvkarleby (60.5°N, 17.4°E), Sweden. A booster reflector of trapezoidal corrugated Al-on-steel was mounted facing north, at an inclination of 25° from the horizontal (see Fig. 2), on the 30th of September 2002. After 12.5 months (380 days), a 10 ×

$10\ cm^2$ sample was cut out from the reflector and its optical properties were measured again.

3.5. Light scattering measurements

Spectrophotometers only assess the *total* hemispherical, the *total* specular ($-6.5 < \theta < 6.5°$, as discussed above), or the *total* diffuse reflectance, and thus give no information about changes in surface isotropy induced by ageing. In order to investigate the spatial distribution of the light scattering from the Al-on-steel reflector material before and after ageing, an in-house angle-resolved scatterometer was used [30]. The scatterometer utilized light from a HeNe laser ($\lambda = 632.8$ nm), which was incident on the sample while a silicon detector was moved in the hemisphere above the sample at a distance of 40 cm. The angular resolution of the instrument was one degree in the azimuth, χ, and zenith, ψ, directions, see Fig. 5.

4. Analysis of optical properties and degradation

4.1. Visual appearance of the reflector material before ageing

The visual appearance of the surface of the Al-on-steel reflector is almost specular, but with small dints across the surface, see Fig. 6. It is believed that they texture originates from the glue that is used in the lamination. The surface is rather easily scratched, but the scratches do not penetrate through the protective PET layer. Fig. 7 shows a photograph of the surface of the Al-on-steel reflector, taken with an optical microscope equipped with a CCD color camera, which was connected to a computer for image analysis. The sample area shown in the photograph is $320 \times 240\ \mu m^2$. Several small defects are visible in the evaporated aluminium foil. The defects on this fresh sample of the Al-on-steel reflector may be starting points for corrosion.

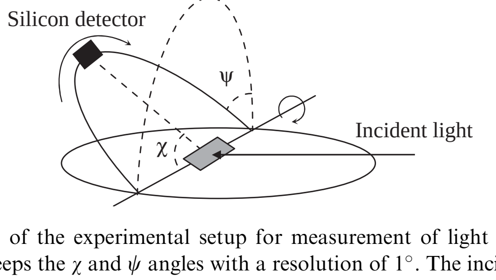

Fig. 5. Schematic picture of the experimental setup for measurement of light scattering from reflector surfaces. The detector sweeps the χ and ψ angles with a resolution of 1°. The incident HeNe laser beam is parallel to the table.

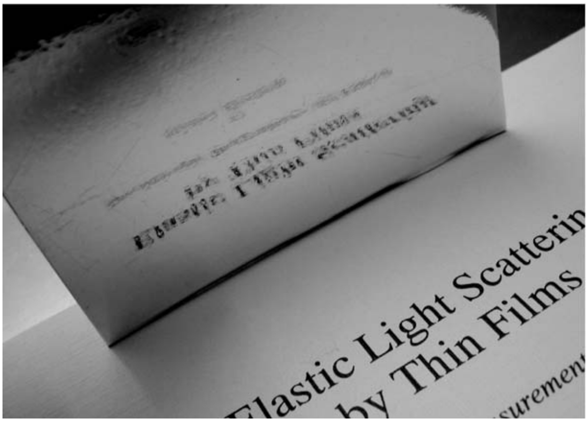

Fig. 6. Visual appearance of the Al-on-steel reflector: a photograph of a thesis on light scattering, reflected in the solar reflector laminate.

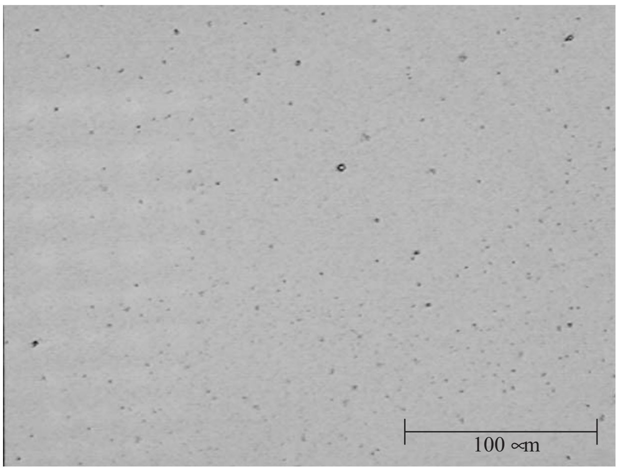

Fig. 7. Photograph of a $320 \times 240\ \mu m^2$ area of the surface of the Al-on-steel reflector, taken with a optical microscope.

4.2. *Reflectance of the reflector material before and after ageing*

Fig. 8 shows the wavelength dependent specular and total reflectance of the Al-on-steel reflector material, measured at near normal angle of incidence. The ISO AM 1.5 solar spectrum [27] and the measured total reflectance of standard anodised aluminium are included in the figure for comparison. The integrated total, specular, and diffuse solar reflectance values of the Al-on-steel sample were 82%, 77%, and 5%, respectively. For the standard anodised aluminium, the corresponding values

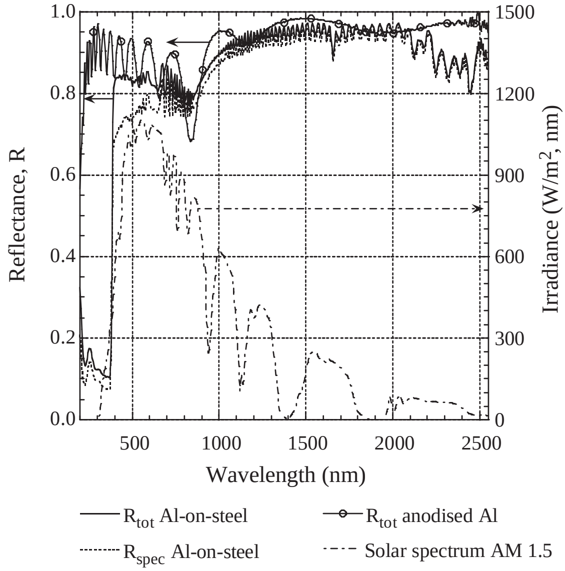

Fig. 8. Wavelength dependent total and specular reflectance of the Al-on-steel reflector material, measured at near normal angle of incidence. The total reflectance of bare anodised aluminium and the solar spectrum are included in the graph.

are 88%, 87%, and 1%. The difference in the total reflectance values of the laminate and the anodised aluminium can be explained by absorption in the PET layer, mainly in the ultraviolet, where there is a sharp cut-off in the reflectance spectrum at 400 nm. This cut-off causes a loss of 3% of the energy available in the solar spectrum.

The reflectance of aluminized plastic films depends on the thickness of the deposited aluminium layer and on the vacuum level during deposition [31]. The evaporation process that was used for deposition of the 20 nm aluminium film on PET has not been investigated further in this work. However, the defects that are visible on the fresh sample of the Al-on-steel reflector (Fig. 7) may stem from insufficient vacuum during deposition or be an indication that the deposited aluminium layer is too thin.

The measured total and diffuse reflectance spectra of the Al-on-steel reflector after 12.5 months of outdoor exposure are shown in Fig. 9. The calculated total solar reflectance was 82% and the specular solar reflectance was 76%. For comparison, the total and specular reflectance spectra of fresh and outdoor aged (9 months) anodised aluminium were measured. While the initial total and specular solar reflectance values for anodised aluminium were 88% and 87%, respectively, the values after 9 months of outdoor exposure were 83% and 79%. Thus the degradation of anodised aluminium is faster than the degradation of the new laminate under outdoor conditions.

Fig. 10 shows the measured total and specular hemispherical reflectance of the Al-on-steel reflector after 1000 and 2000 h of accelerated ageing. The initial total

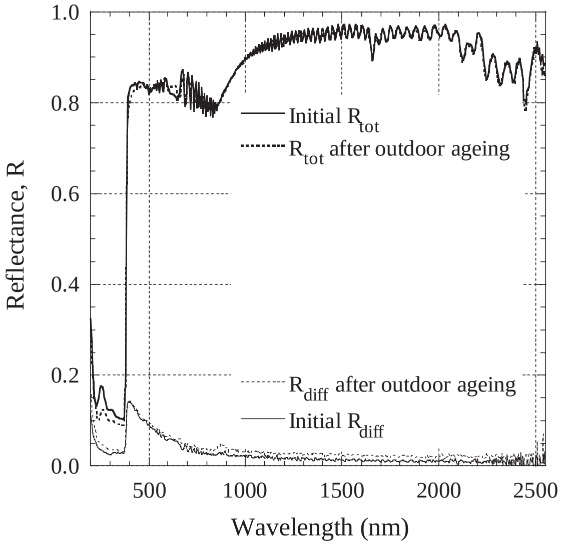

Fig. 9. Measured total and diffuse reflectance of the Al-on-steel reflector, initially and after 12.5 months of outdoor exposure.

hemispherical reflectance are shown for comparison. Note that, while the reduction in the total reflectance is small, the loss of specularity is significant. After 2000 h of accelerated ageing, the total solar reflectance was 75% and the specular solar reflectance was as low as 42%. The low specular reflectance after accelerated ageing is discussed in Section 4.5.

The results of the reflectance measurements on fresh and aged reflector samples are summarised in Table 1. Note the good durability of the reflector under real outdoor conditions, compared to the poor performance in the accelerated ageing test cycle. Worth noting is that no delamination of the reflector material was seen, neither after accelerated ageing nor after outdoor exposure.

4.3. Light scattering

Measurements of light scattering were performed on a fresh sample of Al-on-steel and on an Al-on-steel sample that had been exposed to damp heat for 2000 h in the climate chamber. The scatter distribution from standard anodised aluminium was also measured for comparison. The results for detector sweeps in the χ direction, while keeping $\psi = 0°$, and in the χ direction, keeping $\chi = 0°$, are shown in Figs. 11 and 12. It is evident from Fig. 11 that the distribution of the light scattering from the Al-on-steel reflector in the χ direction changes during the climatic test.

The appearing anisotropy was also seen when the scattering of a laser beam from the aged and the fresh reflector was studied. For the fresh sample, the scatter pattern consisted of a narrow ($\sim 5°$) cone and an isotropic, very faint, background scatter. For the aged sample, the cone was wider ($\sim 8°$), the diffuse background somewhat

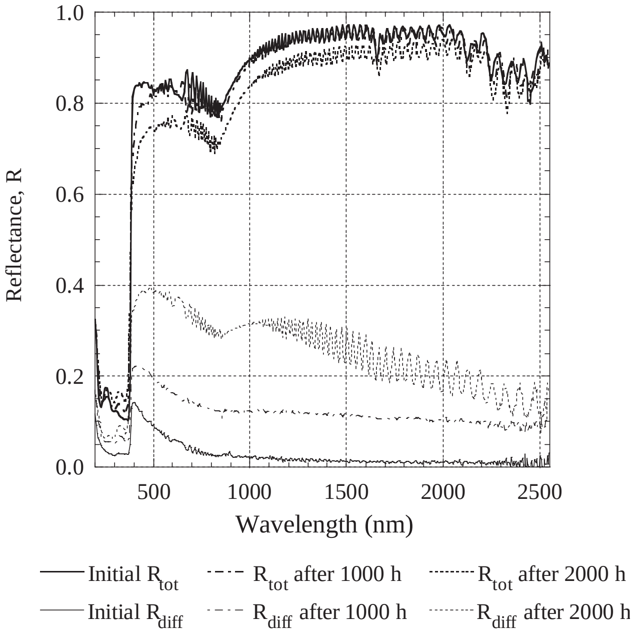

Fig. 10. Total and diffuse reflectance of the Al-on-steel reflector, initially and after 1000 and 2000 h of accelerated ageing.

Table 1
Measured total and specular solar reflectance of the Al-on-steel reflector material, initially, after 1000 and 2000 h of accelerated ageing, as well as after 12.5 months of outdoor exposure

Measured reflectance	R_{tot}^{solar} (%)	R_{spec}^{solar} (%)
Initially	82	77
After 1000 h of accelerated ageing	80	65
After 2000 h of accelerated ageing	75	42
After 12.5 months of outdoor exposure	82	76

stronger, and a band of diffuse scatter that was stronger than the isotropic background appeared in the scatter pattern.

4.4. Surface profiles of fresh and aged samples

Fig. 13 shows the surface profile of the Al-on-steel reflector, before and after accelerated ageing. Note the different scales on the X- and Y-axis. From measurement data, an initial surface roughness of 0.8 μm was calculated. After accelerated ageing, the roughness had increased to 2.1 μm. Several 5000 μm long scans in other directions and across other parts of the samples resulted in approximately the same surface roughness values.

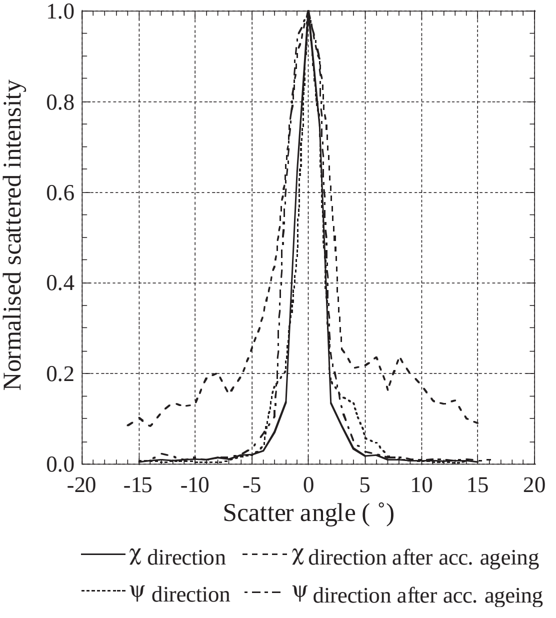

Fig. 11. Scattered intensity measured in the χ and ψ directions from a fresh sample of Al-on-steel and from a sample of Al-on-steel that had been aged for 2000 h in the climatic test chamber. The light source was a HeNe laser beam.

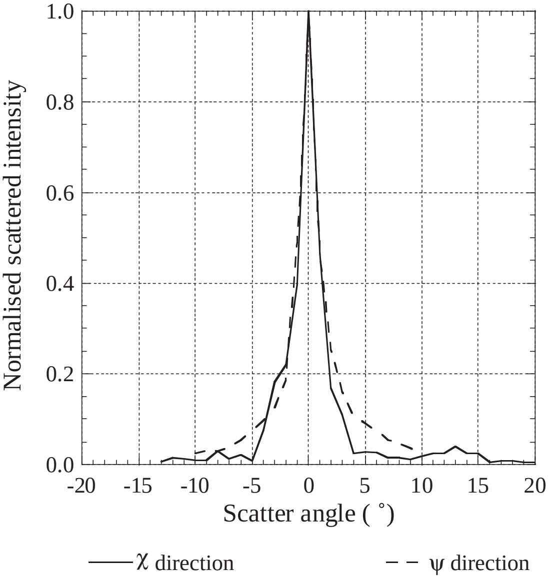

Fig. 12. Scattered intensity in the χ and ψ directions from a fresh sample of standard anodised aluminium. The light source was a HeNe laser beam.

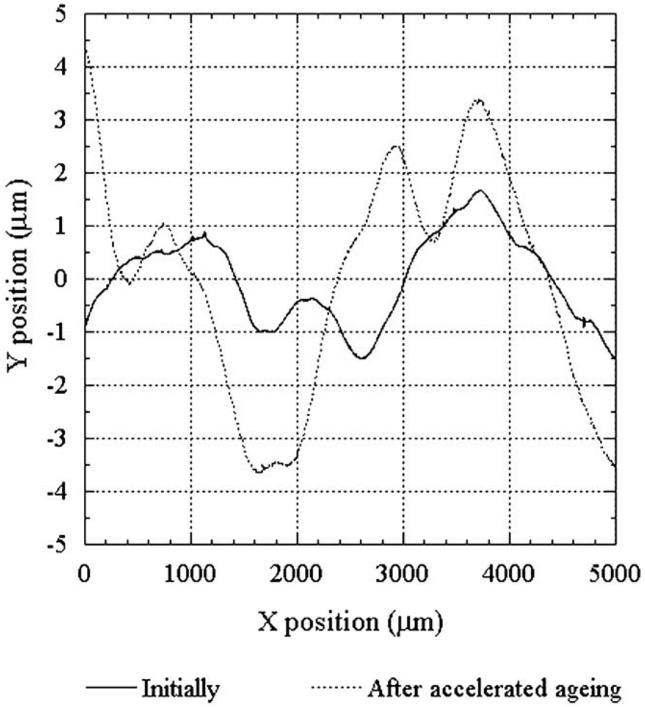

Fig. 13. Profilometer surface scans over 5000 µm of the Al-on-steel reflector material, before and after accelerated ageing. Note the different scales on the X-and Y-axis.

The measured low frequency surface profiles correspond well to the visual appearance of the surface. The initial roughness is believed to be caused by the last lamination step, in which the steel/glue/reflective laminate sandwich is pressed between rolls with a woven fabric. The indents on the surface probably stems from the movement of the glue beneath the reflective laminate in the pressing to places where there is room between the threads in the woven material. The surface roughness of the aged Al-on-steel reflector and the surface roughness was more than twice the roughness before ageing. The increase in surface roughness after accelerated ageing was visible without using the microscope: The dints from the manufacturing process were more visible after ageing. The increase of the surface roughness is believed to be the cause of the broadening of the peak of the forward scattered cone, see Section 4.3. However, it does not account for the anisotropy that was found in the light scattering measurements.

4.5. Analysis of the degradation of the protective coating

In order to find the cause of the increase in the diffusivity and in the anisotropy of the Al-on-steel reflector material after accelerated ageing, we wanted to study the transmittance of the isolated top PET layer of fresh and aged reflectors. This was done by firstly removing the PET/Al/Al/PET laminate from the steel sheet. Then the thin (20 µm) PET layer on the back of the two aluminium layers (the rolled foil and the evaporated film) was gently scratched to puncture the protection of the back surface of the aluminium. After this, the PET/Al/Al/PET sandwich was submerged in a mixture of three parts 14.4 M nitric acid and one part 12.3 M hydrochloric acid, and the aluminium was etched away. The punctured 20 μm PET foil was removed and the 50 μm foil was rinsed, first in ethanol then in trichloroethylene and then in ethanol again, to remove any glue residues from the back of the foil.

The total and diffuse wavelength dependent transmittance, $T_{tot}(\lambda)$ and $T_{diff}(\lambda)$, of the isolated PET foils from the fresh reflector sample, the sample that had been aged for 2000 h in the climate chamber, and the outdoor exposed sample were measured. The results are shown in Fig. 14.

A comparison of the initial total transmittance of the protective PET layer with the transmittance after outdoor ageing show that the PET withstand outdoor exposure well. Actually, the solar transmittance increases slightly, due to a shift in the absorption edge to lower wavelengths. However, the PET that had been exposed to 2000 h of damp heat and radiation in the climate chamber was whitish and had a significantly higher diffuse component of the transmittance than the other samples, although the total transmittance was not drastically reduced. The "noise" that is seen in Fig. 14, at wavelengths longer than 1000 nm is actually interference in the 25 μm thick top PET layer. The distance between the interference fringes perfectly matches the thickness of the PET layer and the distance does not change during

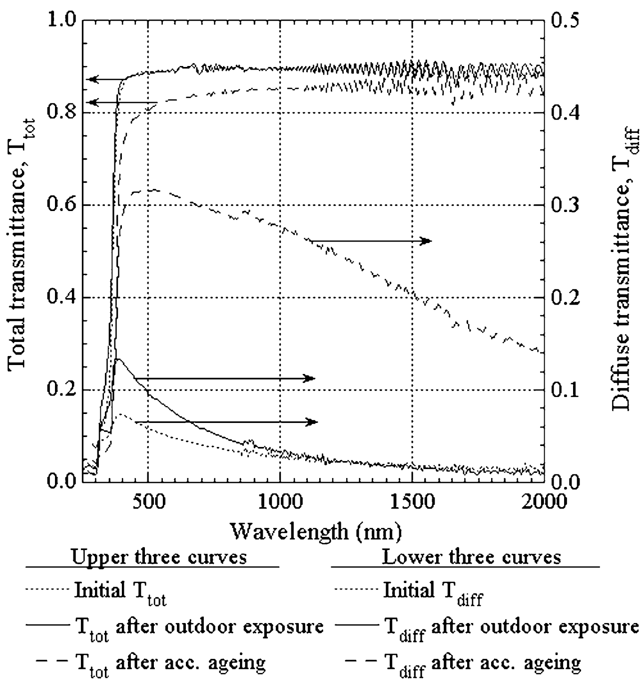

Fig. 14. Measured total and diffuse transmittance of the plastic foil, initially and after 12.5 months of outdoor exposure, as well as after 2000 h of accelerated ageing in the climate chamber.

ageing, which implies that ageing does not have any effect on the thickness or the real part of the refractive index of the PET layer.

The total and diffuse reflectance of the isolated PET foils from the fresh reflector sample, from the sample that had been aged for 2000 h in the climate chamber, and from the outdoor exposed sample were also measured to investigate if the foils were absorbing. In Fig. 15, the results for the fresh sample and the sample that had been aged in the climate chamber are shown. The total and diffuse reflectance of the outdoor aged sample are not included in the graph for clarity, since these two curves largely coincides with the total and diffuse reflectance of the fresh sample. The interference-like, wavelength-dependent variation in the diffuse spectra indicates surface roughness-induced scattering from the polymer interfaces. This effect is pronounced after accelerated ageing, which indicates that changes have taken place in the interface between polymer and aluminium [32].

The wavelength-dependent absorptance, $A(\lambda)$, of the PET foils was calculated using

$$A(\lambda) = 1 - R(\lambda) - T(\lambda). \tag{2}$$

It was found that the integrated solar absorption in the PET layer was 3% for the fresh and outdoor aged sample, while it was 6% for the accelerated aged sample. The decrease in transmittance of the PET layer after accelerated ageing is thus due to an increase in both absorption and reflectance. The measurements of the optical properties of the protective PET foil show that the degradation of the top PET layer fully accounts for the decrease in total reflectance of the Al-on-steel laminate after

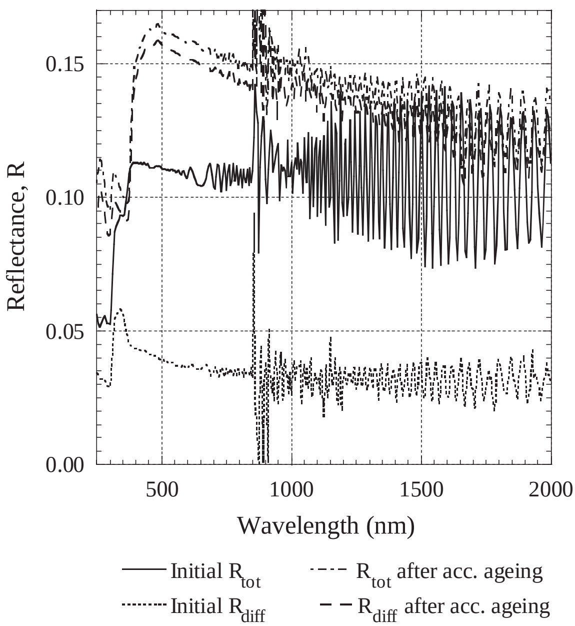

Fig. 15. Measured total and diffuse reflectance of the plastic foil, initially and after 2000 h of accelerated ageing in the climate chamber.

accelerated ageing. The solar weighted transmittance, reflectance, and absorptance of the three examined PET foils are shown in Table 2.

The anisotropic scattering could be understood from analysis of photographs of the aged reflector taken using the optical microscope, see Figs. 16 and 17. Fig. 16 displays the surface of the PET layer. There were clear signs of degradation in the form of cracks in the surface. The pattern was anisotropic, with longer distance between cracks in one of the two orthogonal directions. Hence, the different scattering in the χ and ψ directions. The degradation probably stems from the combination of ultraviolet radiation and cycling at high temperatures. In Fig. 17, the focus of the microscope was on the evaporated aluminium layer beneath the PET layer. The small dark spots (which were interpreted as defects in the aluminium layer) that were visible before ageing (see Fig. 7) had now grown. This shows that the thin evaporated aluminium film degrades fast when the protective coating is damaged. A thicker layer of evaporated aluminium would improve the durability of the specular reflectance, but the longer deposition time associated with a thicker film would result in a more expensive reflector material.

Table 2
Measured transmittance and reflectance of the protective 25 μm protective PET layer, before and after 2000 h of accelerated ageing, as well as after 12.5 months of outdoor exposure

Measured properties of the 25 μm PET foil	T_{tot}^{solar} (%)	T_{spec}^{solar} (%)	R_{tot}^{solar} (%)	A_{tot}^{solar} (%)
Initially	87	83	10	3
After 2000 h of accelerated ageing	80	53	14	6
After 12.5 months of outdoor exposure	87	81	10	3

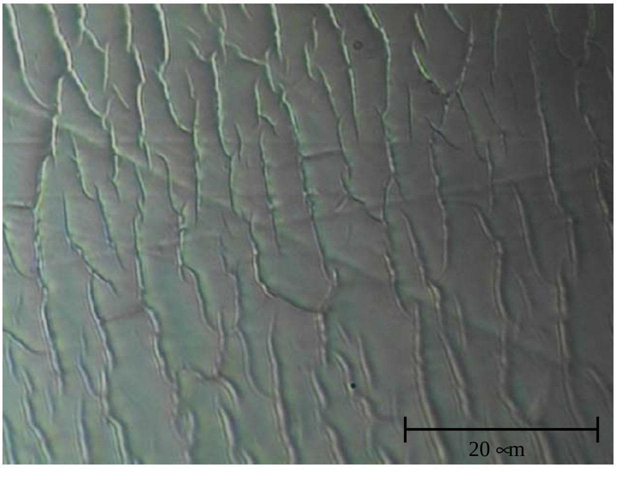

Fig. 16. Photograph of a 64 × 48 μm^2 area of the protective plastic coating on the Al-on-steel reflector after 2000 h of accelerated ageing, taken with an optical microscope.

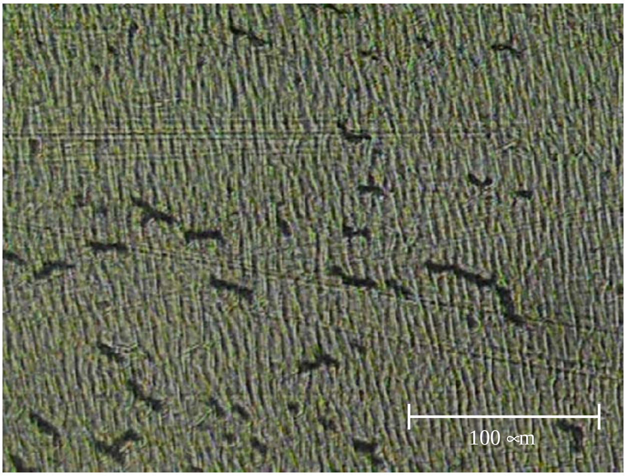

Fig. 17. Photograph of a $320 \times 240\ \mu m^2$ area of the Al-on-steel reflector after 2000 h of accelerated ageing. The photograph was taken with an optical microscope with focus on the evaporated aluminium surface beneath the plastic coating.

5. Performance of the reflector material in concentrating systems

5.1. Optical efficiency of a trapezoidal corrugated booster reflector

The thermal output of the south-facing large area solar collector with a booster reflector of trapezoidal corrugated Al-on-steel, which is installed in Älvkarleby, was measured on a sunny day in June 2003. The measurements were performed both with the reflector functioning and with the reflector covered by a tarpaulin. The result is shown in Fig. 18. The irradiance in the collector plane was also measured, as well as the thermal output of a similar collector with the same inclination (45°) but without reflector. These data are also included in the figure.

Analysis of the thermal energy output from the solar collector with and without functioning reflector shows that the output increases by almost 30% when the tarpaulin is removed from the reflector. At noon, the solar radiation is incident almost parallel to the collector normal and the incidence angle on the reflector is relatively high. Hence, the effective reflector area is relatively small, which results in the relatively low increase in total output at noon. The low increase in thermal output in the late afternoon is due to a low effective concentration ratio of the booster reflector in this configuration, which, in turn is due to the trapezoidal corrugation and to edge effects caused by the small reflector width. If the reflector had been wider, the effective concentration of the test system would have been higher in the afternoon. For some angles of incidence, the corrugation will function as a light trap and radiation will, in unfavourable cases, be reflected several times before reaching the collector plane. If it is not necessary for reasons of mechanical stability, corrugation of booster reflectors is therefore not recommendable.

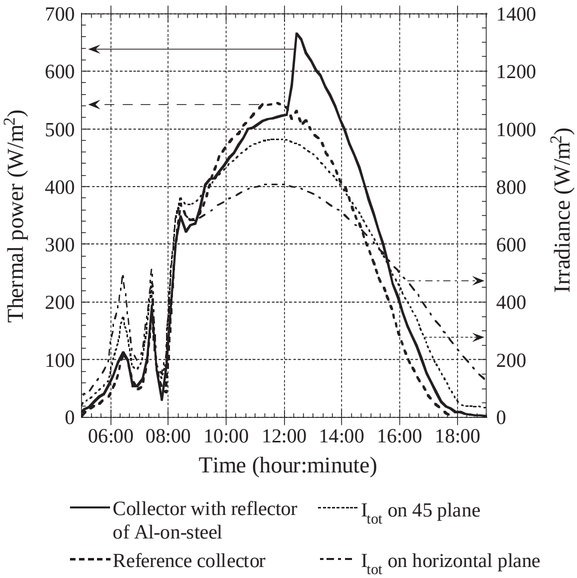

Fig. 18. Measured thermal power from a collector with a trapezoidal corrugated Al-on-steel reflector and a reference system without booster reflector on 26 June 2003. The collectors were mounted side by side in Älvkarleby (60.5°N, 17.4°E), Sweden and facing south with an inclination of 45°. A dark tarpaulin that covered the entire reflector surface was removed at 12:05 pm.

5.2. *Power from solar cells with different reflectors*

The generated current and electrical power as functions of voltage were measured outdoors for solar cells in two geometrically identical concentrating MaReCo [20–22] systems with different reflector materials. The investigated reflector materials were a standard anodized aluminium sheet and the Al-on-steel reflector. Fig. 19 shows the measured current–voltage characteristics and power as a function of voltage. At an ambient temperature of 15°C and a global irradiance of approximately 1000 W/m^2, the Al-on-steel reflector gives a 8% lower output than the anodised aluminium reflector, which is consistent with the difference in reflectance of the two reflector materials (7%) when considering the system geometry and that some radiation hits the module directly, without being reflected.

6. Discussion

6.1. *Differences between outdoor testing and accelerated ageing*

It is a common assumption that solar mirrors are less complex than solar cells and solar thermal absorbers [14], and therefore assessments of the durability of components of solar energy systems have mainly focussed on the active components.

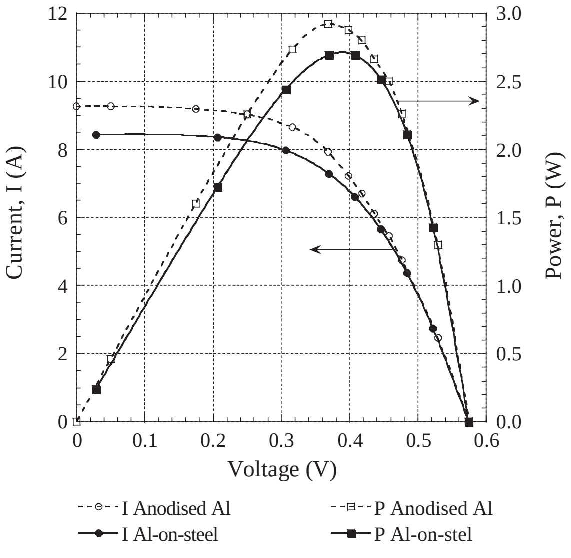

Fig. 19. Measured current-voltage characteristics and calculated power as function of voltage for modules in geometrically identical concentrating systems (MaReCo concentrators) with reflectors of different materials (Al-on-steel and anodised aluminium).

However, as reflector laminates are becoming more frequently used in solar energy applications, their degradation ought to be equally well assessed. Essentially different processes govern the degradation of reflective metallic layers, stiff or flexible substrates, and plastic laminates. Therefore, an understanding of the degradation mechanisms for the different components of a laminate is necessary to be able to predict its lifetime. Likewise, a thorough understanding of the corrosion mechanisms of the Al-on-steel material is necessary in order to interpret our results from accelerated ageing correctly and translate them into technical lifetime under real outdoor conditions. In this work, there was a significant difference between the results from outdoor ageing and accelerated ageing. The Al-on-steel reflector degraded much more when exposed to damp heat for 2000 h than during more than a year of outdoor exposure and the decrease in specular reflectance was disproportionably large after the accelerated tests. The accelerated test has been found to degrade organic laminates disproportionately faster than other types of reflector materials [33]. This indicates that testing at more intense ultraviolet radiation than that of real sunlight, in combination with temperatures as high as 80°C, is too tough for this kind of reflector. Therefore, we will not draw any conclusions from the accelerated ageing test about long-term performance of the Al-on-steel reflector material. During outdoor exposure, however, the laminate protected the reflective aluminium surface from air pollutants, thus prolonging the lifetime of this type of reflector compared to bare metal reflectors, such as anodised aluminium.

At the site of the outdoor ageing tests in Älvkarleby, Sweden, the air pollution levels and the salinity in the air are fairly low, since the site is located 10 km from the nearest industry and 10 km from the Baltic Sea, which has brackish water. Therefore, we do not know whether the material withstands exposure to higher concentrations of pollutants. Environmental tests, with controlled concentrations of air pollutants, in a test chamber would therefore be of interest to investigate if the reflector material withstands outdoor exposure in industrial areas. Alternatively, samples of the reflector could be mounted in areas with different types of heavy industries, which has been done elsewhere [16].

In general, degradation of materials does not depend linearly on variables such as concentration of air pollutants, temperature, time, humidity, or radiation levels. There may be threshold value of these variables, below which essentially no degradation takes place. For laminated reflectors, the degradation of the optical properties often depends more on the specific climatic conditions than on exposure time [33].

6.2. Cost of the Al-on-steel reflector

A self-supporting trapezoidal corrugated aluminium sheet costs about € 16 per m^2. The price of a flat mass produced Al-on-steel reflector is estimated by the manufacturer to €8 per m^2. The additional cost for corrugation, if this is desired, is estimated to € 3.30 per m^2.

Since the large scale cost of the new Al-on-steel laminate is expected to be 50% lower than the cost of an anodised aluminium reflector, and the reflectance of the new material is almost equally high as the reflectance of anodised aluminium, the Al-on-steel laminate would be the most cost-effective alternative.

6.3. Utilisation of the Al-on-steel reflector under a protective glazing

When the Al-on-steel reflector is used in the MaReCo collectors in Hammarby sjöstad, it will be protected by a cover glass. The cover glass is primarily intended to protect the hybrid absorber and to reduce convective and radiative heat losses, but it will also protect the Al-on-steel reflector from the rain, snow, dust and air pollutants, which may increase the durability of the reflector. However, the glass will prevent natural ventilation of the collector, and although the reflector trough is not thermally insulated, the reflector temperature may reach levels close to those in the climatic test chamber. Therefore, precaution should be taken to allow for sufficient ventilation around the reflector troughs.

7. Summary and conclusions

A newly developed laminated aluminium-on-steel reflector with a protective layer of PET was evaluated. The advantage of this material is that it combines the relatively high specular reflectance of aluminium with the stiffness of steel, which makes it self-supporting and easy to shape into any concentrator geometry. The optical properties and degradation of the reflector were investigated and its system performance was tested in two solar energy applications: as a booster reflector for a solar thermal collector and as a concentrator in a photovoltaic system with MaReCo geometry.

Reflectance measurements on fresh Al-on-steel samples showed that the reflector had good optical properties for solar concentrator applications prior to ageing. It had an initial solar reflectance of 82% out of which 77% was specular. Results from reflectance measurements after more than a year of outdoor exposure indicate that the aluminium-laminated steel reflector has good durability in an outdoor environment, probably because of the plastic coating that protects the evaporated aluminium foil from moisture and air pollutants. However, the total reflectance decreased significantly and the light scattering became anisotropical when the material was exposed to damp heat and ultraviolet radiation in a climatic test chamber. It was found that the PET coating did not withstand the accelerated testing and that cracks in the PET layer caused the scattering. Therefore, the material may not be suitable as an internal reflector or in other applications where it may be exposed to high temperatures. However, the optical properties of the Al-on-steel reflector remained unchanged during one year of outdoor exposure in Sweden. Thus, given that the large-scale production cost of the laminate will be as low as the manufacturer expects, the material shows a potential as a cost-effective reflector in low-concentrating solar thermal and photovoltaic applications.

Acknowledgements

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