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DEVELOPMENT OF A TEST METHOD FOR THE INVESTIGATION OF THE ABRASIVE EFFECT OF SAND PARTICLES ON COMPONENTS OF SOLAR ENERGY SYSTEMS

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ABSTRACT: Currently, there is no appropriate, standardized, accelerated test method to investigate the abrasion resistance of components of solar energy systems under sand storm conditions. Therefore, this paper deals with the development of a test method for the investigation of the sand abrasion mechanism on selected solar technical components. For this purpose, first, the mechanisms of surface damage induced by trickling sand are experimentally investigated. The designed method based on ASTM D968-05 enables to describe the sand abrasion mechanisms on aluminum reflectors and solar glasses. Also, differences in the abrasion resistance of the samples are revealed. In addition to changes in their optical properties, an increased surface roughness can be determined. Depending on the impact angle, hardness of the exposed material, sand trickling mass and sand concentration, different surface changes are caused. The concentrated particle stream led to strong abrasive damage on the reflector surfaces, whereas glasses show a better abrasion resistance to trickling sand because of their higher hardness. The second, horizontal test method designed according to the sandblasting principle allows a more realistic investigation of the sand abrasion process on samples under strong wind conditions. The low, sand-laden air flow causes less abrasive damage on the reflector surfaces.
Keywords: sand abrasion, abrasion resistance, sand trickling method, sandblasting

1 INTRODUCTION

The technical potential of solar energy in desert regions is enormous [9]. However, sand storms in these regions can seriously affect the surfaces of components of solar energy systems. The interaction between sand and wind has a sand blasting character [2] and results in different, irreparable wear mechanisms. One dominant type of several general wear mechanisms is abrasion [3]. In case of solar panels, which are increasingly used in desert regions, abrasive damages of the solar glass surface and the accompanying decrease in the degree of transmittance can lead to high yield losses.
Therefore, testing the abrasion resistance of solar technical components under sand storm conditions is of crucial importance and a major contribution to the use of solar energy systems in desert regions. An increasing number of requests from PV module manufacturers for the resistance of their modules against sand abrasion shows that this issue is taken seriously. However, there is currently no standardized, accelerated test method to investigate the abrasion resistance of components of solar energy systems under sand storm conditions.
The major objectives of this paper are:

- Investigation of the sand abrasion mechanism on different types of aluminum reflectors and solar glasses
- Comparison of different test methods for accelerated abrasion tests with sand
- Identification and specification of appropriate site-specific parameters (such as sand composition, temperature or wind speed) in order to perform sand abrasion tests under sand storm conditions in deserts.

2 APPROACH

Initially, existing standards, methods and scientific publications about sand abrasion tests were reviewed on their relevance for the usage in solar technology. After a systematic literature research and a summary of the characteristic data of sand abrasion tests, four different test methods can be determined (see Fig. 1) [1; 4; 5; 7; 6; 10;11].

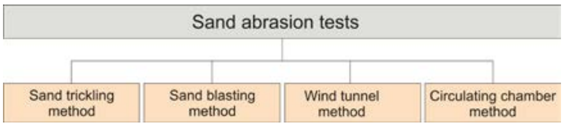

Figure 1: Four different methods of sand abrasion tests

2.1 Sand trickling method

Methods according to the sand trickling standards ASTM D968-05 and DIN 52348 are usually used in the industry to investigate the abrasion resistance of surface coatings such as paints and varnishes [8], as well as glasses or synthetics [6]. Similar to the standard ASTM D968-05, different types of aluminum reflectors and solar glasses were tested. In this abrasion test, sand is trickled from a specific height onto a sample. By applying the law of freefall, the impact velocity is below 5.7 m/s.
The influence of the trickling sand particles on the surface materials is examined under variation of both the sand quantity and the impact angle. By varying the impact angle, the following two types of wear can be studied: impact wear (impact angle $\alpha = 90°$) and diagonal wear ($0° < \alpha < 90°$).
For the abrasion tests, quartz sand with a grain fraction of 0.5 to 0.71 mm according to the German standard DIN 52348 is used [6]. In Fig. 2, the actual sand trickling process is exemplified on a reflector sample at an impact angle of 45°.

Figure 2: Focused sand stream at an impact angle of 45°

The abrasive damages on the surface of the tested reflector samples according to the test matrix are shown in Fig. 3. Depending on the impact angle and the amount of trickling sand, the size and the shape of the abrasive spot on the reflector surface, and thus the degree of abrasion varies.

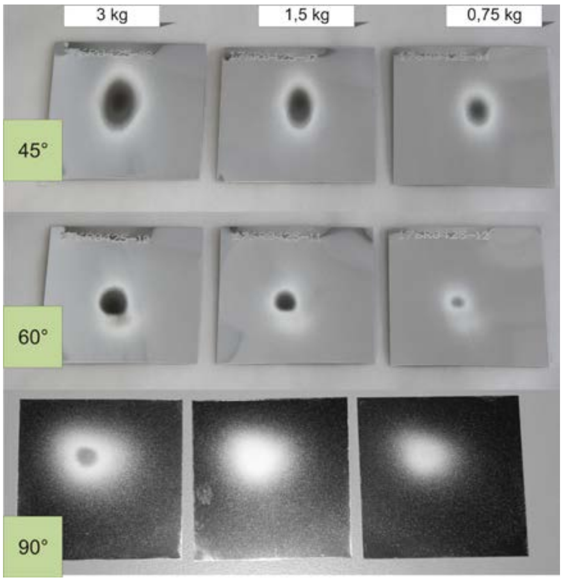

Figure 3: Visible damages on the reflector surface

The impact and diagonal wear cause different types of damages on the reflector surface which are due to different movements (bouncing, sliding) of the sand particles.

2.1.1 Characterization methods

A detailed characterization of the material surfaces was performed before and after the sand trickling test. For the characterization of the selected solar glass and aluminum reflector samples, several measuring instruments were used (see Table I).

Table I: Measuring instruments and the corresponding surface material parameter

Measuring instrument	**Surface material parameter**
Contact angle measuring system	Wettability
Fourier transform spectrometer	Spectral hemispherical transmittance and reflectance
Auger electron spectroscopy	Chemical composition
Light microscope	Visible change
Atomic force microscope	Topography and roughness

2.1.2 Results of the optical characterization

As the visible damages on the reflector surface indicate, the solar reflectance of all samples strongly degrade with both the increasing amount of trickling sand and the decreasing impact angle (see Fig. 4). The solar transmittance of the abraded solar glasses in Fig. 5 shows similar results.

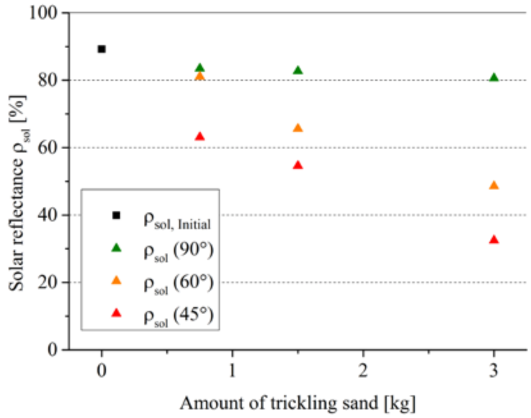

Figure 4: Solar reflectance of the abraded reflector samples

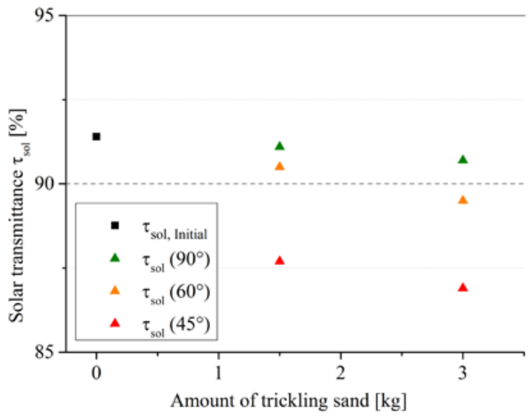

Figure 5: Solar transmittance of the abraded solar glass samples

The losses in transmittance and reflectance are caused by the increasing roughness of the tested material surfaces due to increasing the amount of trickling sand. The aluminum reflectors show an additional phenomenon on the surface. In addition to the increasing roughness, the surface becomes darker where the sand stream hits it. The analysis of the surface composition of this spot by Auger electron spectroscopy (AES) shows that the reflector surface layers are removed to the anodized layer. The dark spot on the reflector surface results in a higher absorption of the incident light beam. In total, both surface phenomena cause a high loss in reflectance. For this reason, the losses of the solar reflectance of the reflectors are comparatively higher than the losses of the solar transmittance of the glasses.

2.1.3 Degree of abrasive damage (abrasion)

In order to make statements about the degree of the abrasive damage of a reflector or a glass surface, the normalized loss of reflectance $V_{Reflectance}$ or the normalized loss of transmittance $V_{Transmittance}$ are calculated. For this purpose, the following formulas are used:

$$V_{Reflectance} = \frac{R_0 - R}{R_0} \cdot 100\ \%$$

$$V_{Transmittance} = \frac{T_0 - T}{T_0} \cdot 100\ \%$$

with

R_0 / T_0 Solar reflectance/transmittance before the sand abrasion test

R / T Solar reflectance/transmittance after the sand abrasion test

As a result, the following degrees of abrasion can be determined for tested material surfaces (see Table II).

Table II: Degree of abrasion of an aluminum reflector and a solar glass

	Impact angle			**Amount of sand**		
	45°	60°	90°	0.75 kg	1.5 kg	3 kg
				Degree of abrasion [%]		
Reflector				29.3	38.8	63.6
				9.1	26.5	45.5
				6.4	7.3	9.6
Glass					4.1	4.9
					1	2.1
					0.3	0.7

An increase of the degree of abrasive damage is associated with both an increasing amount of trickling sand and a decreasing impact angle. The better abrasion resistance of the solar glasses is due to their higher hardness compared to the aluminum reflectors.

2.1.4 Summary

The sand trickling method was used to analyze the degradation mechanism of sand abrasion on aluminum reflectors and solar glasses. In addition to changes in the optical properties, an increased surface roughness can be determined by the impact of sand particles. The degree of surface abrasion depends on:

- Impact angle
- Sand concentration
- Amount of trickling sand
- Hardness of the material

Basically, the sand trickling method is an extremely accelerated degradation test for the tested aluminum reflector samples, since they show a high level of abrasive damage on the surface.
However, this accelerated abrasion test allows to examine the sand abrasion resistance of different surface materials rapidly. It is possible to detect differences between the materials with respect to their resistance in abrasive environments. In terms of a test method to investigate the abrasion behavior of sand on components of solar energy systems under realistic sand storm conditions, the following improvements can be considered:

(1) Creating a sand-laden air flow
(2) Increasing the particle velocity
(3) Reducing the sand concentration
(4) Homogeneous distribution of the impacting sand particles on the sample surface

2.2 Sand blasting method

The sand blasting method realizes the above-mentioned improvements. The sand particles float with a measured air flow velocity of 11.7 m/s (Beaufort 6) onto the sample surface. In Fig. 6, the schematic set-up of this method is illustrated.

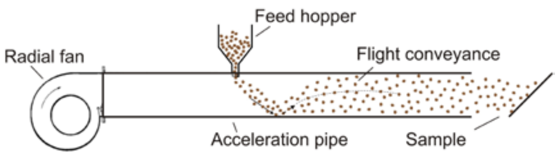

Figure 6: Schematic set-up of the main components of the sand blasting method

The abrasion tests were only performed under an impact angle of 45°. In Fig. 7, the sand blasting process is exemplified on a reflector sample. It shows that the surface is homogeneously blasted with sand. As a result, the abrasive damage of the tested reflector surfaces is lower and the reflectance is not greatly reduced.

Figure 7: Sand blasting method on a reflector ($\alpha = 45°$)

2.2.1 Results of the optical characterization

Fig. 8 shows that the loss in reflectance is higher the more sand is blasted onto the sample surface.

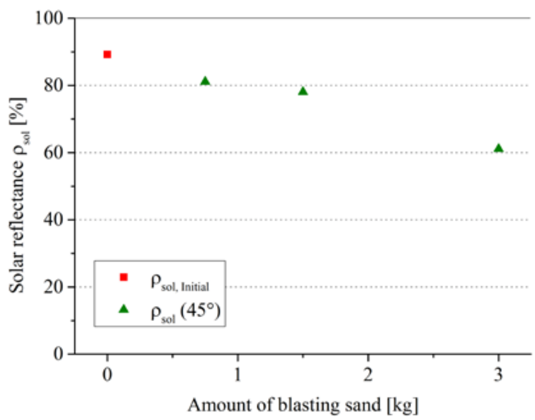

Figure 8: Solar reflectance of abraded reflector samples

However, the solar reflectance of the abraded reflector samples does not decrease as strong as in the sand trickling method. This means, the degree of abrasion is weaker which is confirmed by indicating the normalized loss of reflectance (see Table III).

Table III: Degree of abrasion of aluminum reflectors after the sand trickling method (A) and after the sand blasting method (B) at an impact angle of 45°

	Amount of sand		
	0.75 kg	1.5 kg	3 kg
	Degree of abrasion [%]		
Reflector (A)	29.3	38.8	63.6
Reflector (B)	9.1	12.4	31.5

With a comparable amount of sand, the loss of reflectance of the abraded reflector samples is much lower than in the sand blasting method, although the velocity of the sand particles is higher. This is due to the lower and thus more realistic concentration of sand particles in the air stream.

3. CONCLUSION

Both examined abrasion methods allow analyzing the degradation mechanism of sand abrasion on different surface materials and classifying the abrasion resistance of different materials towards sand. The influence of sand particles on the optical properties of the sample surfaces can be very precisely detected by measuring the spectral hemispherical reflectance and transmittance. In addition to changes in the optical properties, an increased surface roughness due to the impact of sand particles can be determined. Depending on the impact angle, the hardness of the exposed material, the amount of sand and the sand concentration, different surface changes are caused.

In the sand trickling method, the tested reflectors indicate very strong surface damages due to the concentrated particle stream. In contrast, the investigated solar glass samples turn out to be quite resistant to sand abrasion. However, this test method is an extreme test for the examined reflector samples, because the surface layers are removed to the anodized layer. Therefore, the sand trickling method cannot be expected to be appropriate for the investigation of sand abrasion under realistic sand storm conditions.

In contrast, the sandblasting test method allows a more realistic study of sand abrasion on samples under strong wind conditions. Due to the low particle load in the rapidly moving air flow, comparatively weaker abrasion damage on the sample surface is caused. Instead of hitting the sample surface in a concentrated way, the sand particles distribute in the acceleration pipe before they hit the sample. Compared to the sand trickling method, the particle velocity in the sand blasting method is almost doubled.

A problem of accelerated abrasion tests with sand is the lack of data on exact particle concentrations in real sand storms in deserts. Further, in reality, there are other factors (e.g. temperature, surface characteristics (e.g. Young's modulus), particle size and particle shape) which can influence the degree of abrasive damage on a surface.

Since there is currently no standard method for performing accelerated abrasion tests on components of solar energy systems under desert conditions, the military standard MIL-STD-810G may be used as a guideline.

4. OUTLOOK

In addition to reflectors and solar glasses, other components of solar energy systems, such as back sheets, shall be subjected to a sandblasting test in order to analyze their resistance against sand abrasion. Also, the investigation of entire solar modules or major system components is desirable. By performing sand abrasion tests on solar modules, effects on electrical functionality, leakage of sealants and surface degradation can be investigated.

For conducting such tests, the experimental set-up must be dimensioned accordingly which is associated with both a high process effort and high investments. It is therefore proposed to test only a small part of a solar module. Yet, in order to realize a comprehensive investigation of sand abrasion on entire solar modules, sand abrasion tests at several representative spots on the module should be carried out.

In reality, there are interactions between the surface damages of samples caused by sand abrasion and other environmental factors, such as UV radiation or temperature which strongly influence the aging behavior of the samples. Therefore, it is recommended to consider the influence of these degradation factors. This could be done by developing sequential test methods, e.g. to analyze the influence of polymer embrittlement on abrasion resistance.

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