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Contact Cleaning of Polymer Film Solar Reflectors

Christopher Sansom[1, a)], Aránzazu Fernández-García[2], Florian Sutter[3], Heather Almond[1], and Peter King[1]

[1] *Global CSP Laboratory, Cranfield University, Bedfordshire MK43 0AL, UK.*
[2] *CIEMAT-Plataforma Solar de Almería, Senes Road, Km. 4.5, P.O. Box 22, E04200 Tabernas, Almería, Spain*
[3] *DLR, Institute of Solar Research, Plataforma Solar de Almería, Senes Road, Km. 4.5, P.O. Box 44, E04200 Tabernas, Almería, Spain*

[a)] Corresponding author c.l.sansom@cranfield.ac.uk

Abstract. This paper describes the accelerated ageing of polymer film reflecting surfaces under the conditions to be found during contact cleaning of Concentrating Solar Power (CSP) collectors in the presence of dust and sand particles. In these situations, contact cleaning using brushes and water is required to clean the reflecting surfaces. Whilst suitable for glass reflectors, this paper discusses the effects of existing cleaning processes on the optical and visual properties of polymer film surfaces, and then describes the development of a more benign but effective contact cleaning process for cleaning polymer reflectors. The effects of a range of cleaning brushes are discussed, with and without the presence of water, in the presence of sand and dust particles from selected representative locations. Reflectance measurements and visual inspection shows that a soft cleaning brush with a small amount of water can clean polymer film reflecting surfaces without inflicting surface damage or reducing specular reflectance.

INTRODUCTION

The performance of parabolic-trough CSP plants is critically dependent on the optical efficiency of the solar field, including the reflectance of the solar collector mirrors. Generally made of silvered-glass of up to 4 mm thickness, the mirrors and their tracking and supporting structures are also a significant capital cost. Alternative reflecting materials are available [1], but their robustness and durability has yet to be proven. One of the important aspects that may degrade the mirror surface is the cleaning task, mainly when it involves a contact device, which sometimes is indispensable to remove a soiling layer that is strongly attached [2].

This work presents the results of experiments carried out to investigate the robustness of commercially available silvered polymer film reflectors under conditions of contact cleaning. The results clearly show that commercially available polymer film can easily be damaged under existing contact cleaning regimes. As a result, a range of cleaning brushes was tested and a new and effective contact cleaning process was developed. The results of reflectance measurements and visual inspection indicate that it is possible to remove sand and dust particles from polymer film collectors with a suitably benign cleaning process.

METHODOLOGY

The experiments were carried out at both a joint laboratory between CIEMAT and DLR at the Plataforma Solar de Almería (PSA) in Spain and Cranfield University in the United Kingdom, using different abrasion test equipment and optical measurement techniques in order to maximize the validity of the results. The techniques used in this work for simulating contact cleaning are shown in Fig. 1 below. Four different cleaning brushes with a range of bristle hardness were used, soiled with both Quartz-Silica (MIL-E-5007C) and samples of dust and sand taken from Europe, Middle East, and the Americas. Cleaning both with and without soiling was investigated. The PSA tests

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were performed in accordance with ISO 11998 [3] using an Erichsen model 494 machine, which simulates CSP plant reflector cleaning with a DIN 53778/B5 brush.

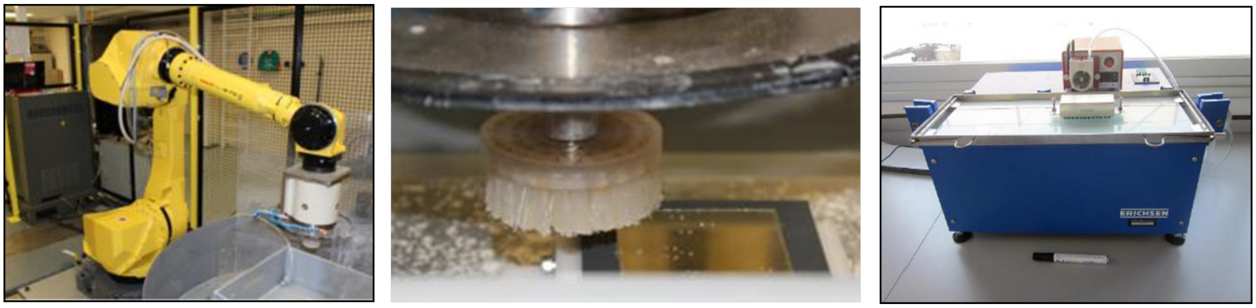

FIGURE 1. Cleaning simulation tools: Fanuc robot (left) with rotary brush (centre) and the Erichsen 494 (right)

The Cranfield cleaning simulations used a FANUC Robot M-710i with a rotary head at 300 rpm with an ASTM 2486 [4] standard brush unit and linear speed of 285 mm/min for 400 cycles. Optical measurements of both hemispherical reflectance and monochromatic specular reflectance were performed at both research centres, using a Perkin Elmer Lambda 1050 spectrophotometer with a 150 mm integrating sphere and a Devices and Services (D&S) 15R portable reflectometer at the PSA; and a Jasco-670 spectrophotometer with a 60 mm integrating sphere and a Condor portable reflectometer at Cranfield; instruments that include those shown in Fig. 2 below.

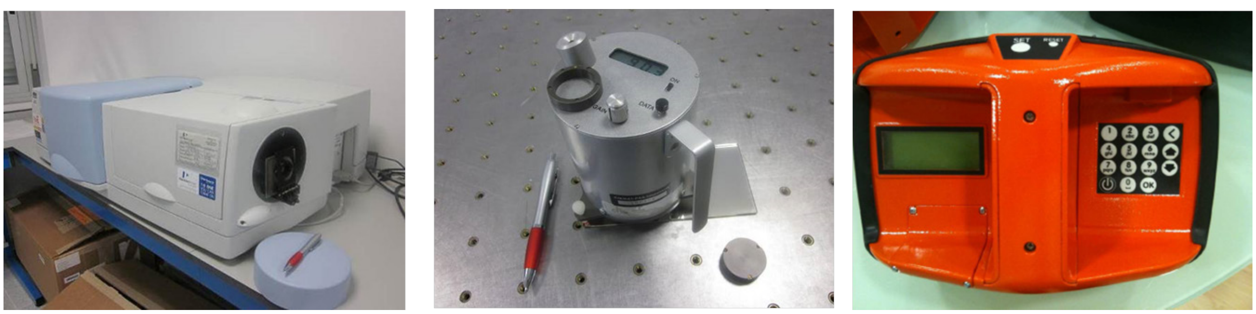

FIGURE 2. Perkin Elmer 1050 spectrophotometer, D&S 15R-USB and Abengoa Condor reflectometers

The Effect of Existing Contact Cleaning Methods

Despite the addition of hard coatings, the durability of polymer film reflectors under contact cleaning regimes is less than that of glass reflectors when used in CSP applications. Using hard bristle brushes with demineralized water the film exhibits visible scratches and a significant reduction in monochromatic specular reflectance whereas the spectral hemispherical reflectance remains unchanged. An example of this is shown in Fig. 3 and Fig. 4, with results from the PSA. Note that the reduction in specularity is non-linear under hard abrasion conditions, with the reflectance tending to stabilize after a time represented by 40-50 cleaning cycles. 100 cycles correspond to approximately 1.9 years of operation in a CSP plant with two weeks cleaning intervals assuming that every spot of the surface is being cleaned with two cycles.

New Benign Contact Cleaning Regime

The next step in the present research study consisted on optimizing the cleaning method to avoid, or at least minimize, the damage in the mirror surface under analysis. This section includes a description of the methodology followed and the results obtained in the experiments.

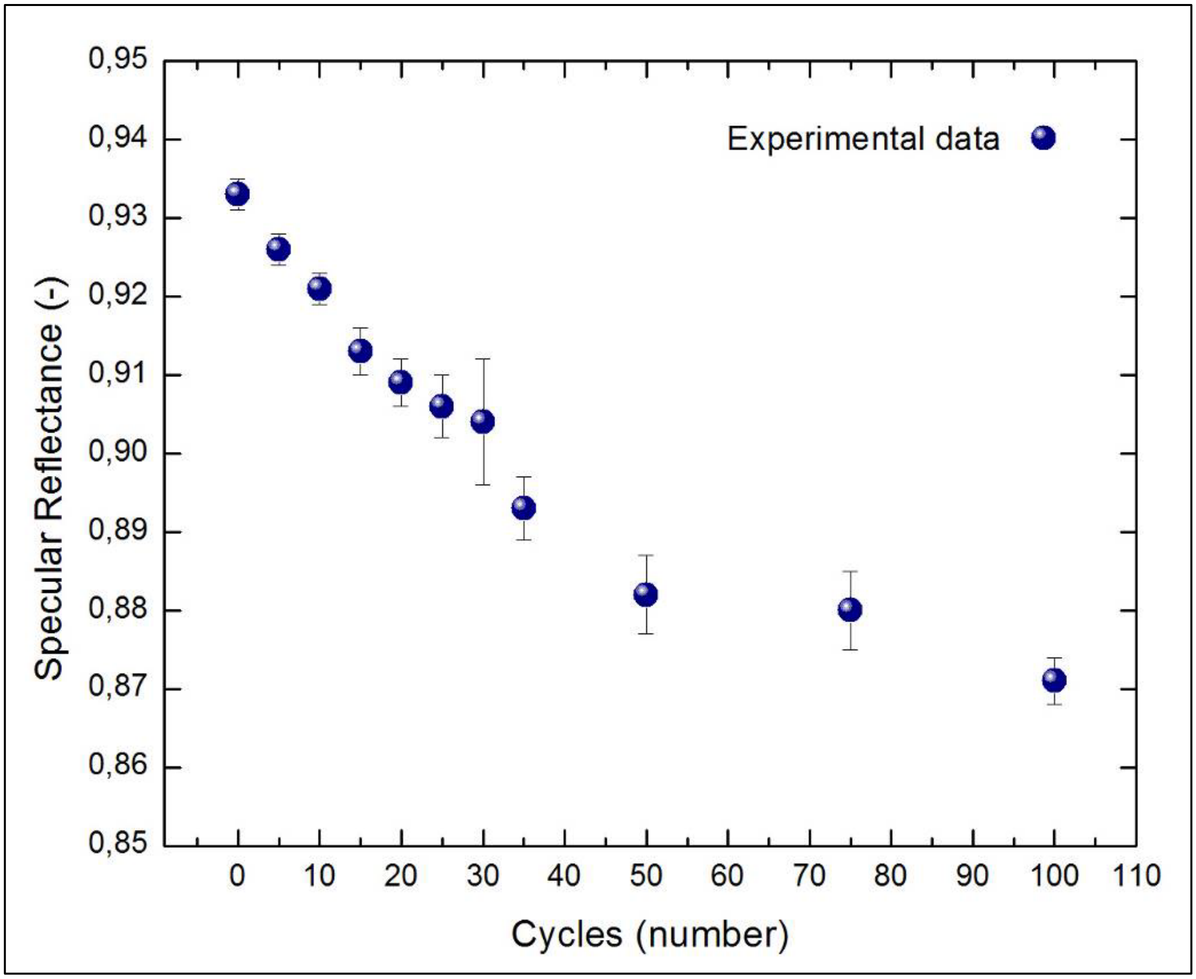

FIGURE 3. Monochromic specular reflectance after 100 cycles of cleaning abrasion test

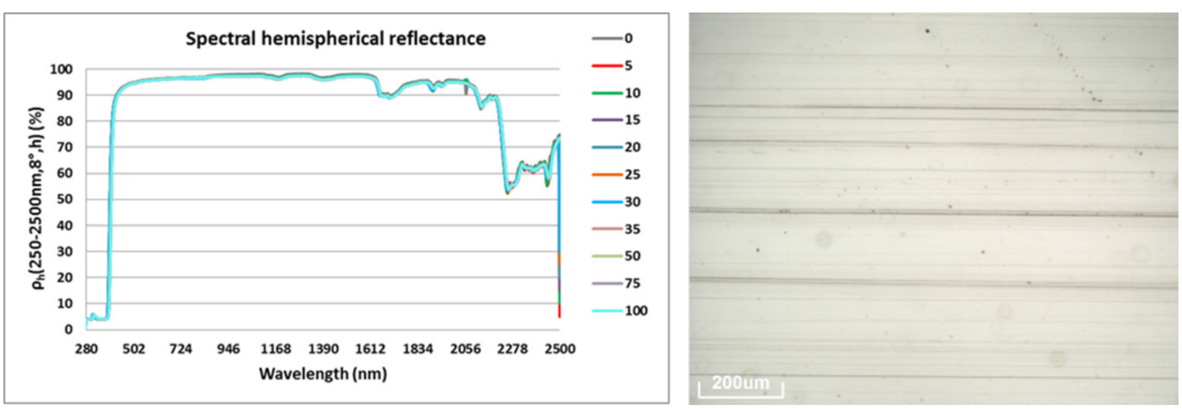

FIGURE 4. Hemispherical reflectance after 100 cycles and scratches after 10 cycles (cleaning abrasion test)

Sample Preparation

Samples of SkyFuel ReflecTech®PLUS polymer film were cut to a size of 3x3 cm² square. Three brushes were used (nominally labelled as “soft”, “medium”, and “hard” in terms of the overall hardness of the brush), and sand was used that had previously been collected from three locations (described as “Sahara”, “Arizona”, and “PSA”). In preparing the samples for abrasive cleaning it was necessary to develop a technique to deposit a suspension of sand in demineralized water on each sample of polymer film, a non-trivial task owing to the highly hydrophobic surface coating on the film. Fig. 5 below illustrates the sands and brushes used and the sample preparation under development.

FIGURE 5. Brushes with fixings to Fanuc robot, examples of sand samples, and samples under preparation

Contact Cleaning Experimental Set-up

Samples were analyzed prior to any soiling and abrasive testing, measuring hemispherical reflectance using the spectrophotometer and specular reflectance using the Condor reflectometer. Then each sample was placed on the sample table of the Fanuc robot in turn, and a series of simulated contact cleaning runs performed. Some samples were used to set up the brush height, then the majority of the experiments were performed as we varied the brush hardness and the sand type. Runs were also performed to investigate whether the presence of water was necessary, and additional runs were also performed without sand. Following each run, reflectance measurements were repeated and the samples were visually inspected for signs of surface damage. All measurements of specular reflectance were taken at six wavelengths (435, 525, 650, 780, 940 and 1050 nm), but only a representative sample of the results are shown below.

Results

The results shown in Fig. 6 below clearly show the influence of both water and brush hardness on the specular reflectance drop of the polymer film reflector samples after the testing of 400 cycles, which approximately corresponds to 7.6 years of operation in a CSP plant (assuming typical washing cycles of two weeks). As can be seen in the Fig. 6a the presence of water in the cleaning processes reduced surface damage, though not completely. However the brush hardness was shown to play a significant role (see Fig. 6b), with surface damage reducing as the brush hardness decreased. The role played by the soiling medium, in this case comprising three sand samples, is more complex as shown in Fig. 7a below. All three sands cause a loss of reflectance in the polymer film, as indeed happens when no sand is present.

We conclude that the presence of water and the softness of the brush are the main influences on the specular reflectance, with the sand characteristics playing a secondary role. This prompted an analysis of the three sands used in the experiment. Sand hardness was determined using a nano-indentation technique with the results shown in Fig. 7b. There is little to choose between the mean hardness of the three sands tested, with the most significant feature being the narrower spread in values from the samples of sand from the PSA.

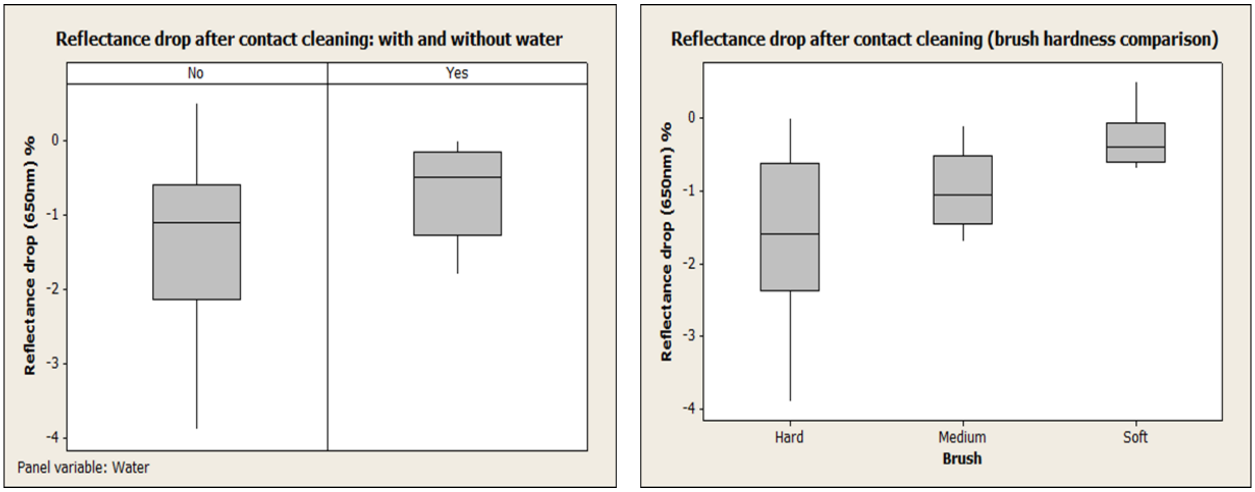

FIGURE 6. Reflectance drop for all samples, showing influence of water (a) and brush hardness (b) after 400 cycles

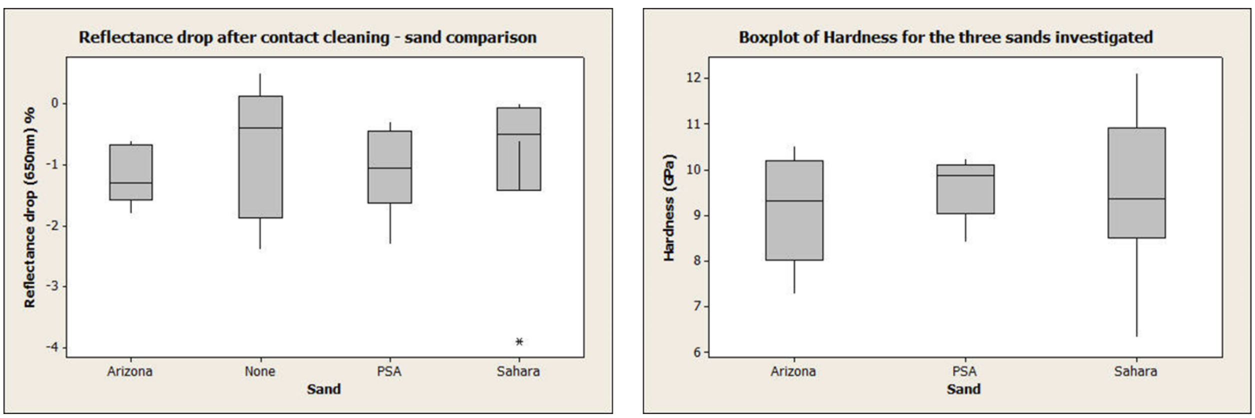

FIGURE 7. (a) Plot of reflectance drop for each sand and (b) measurements of sand hardness after 400 cycles

Despite their similar hardness, individual sands appeared quite distinct when examined visually. Fig. 8 below highlights these differences. The Arizona sand comprises small sand particles of the order of 1-10µm, not unlike the PSA sand in general although the PSA sand does contain some larger particles.

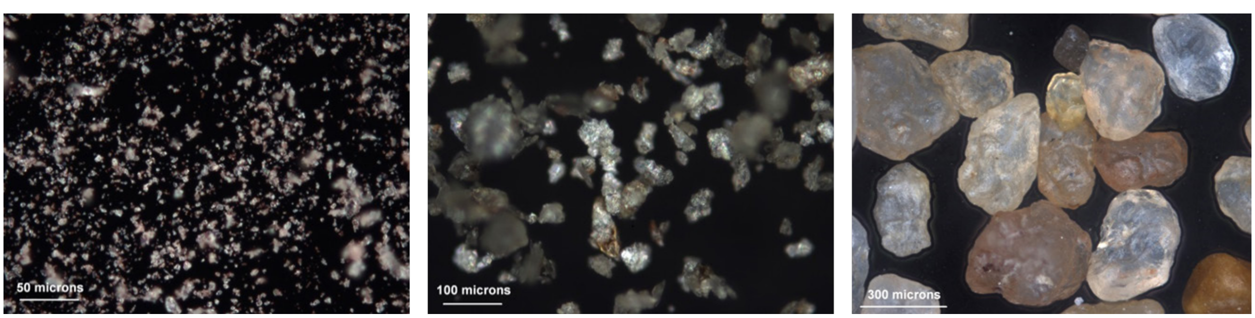

FIGURE 8. SEM micrographs of the three sands designated Arizona (left), PSA (centre), and Sahara (right)

The Saharan sand is very different, with particles sizes of the order of 100μm+ and with more rounded edges on average. Yet for all three sands, Figure 6 shows that we have the capability to remove the particles from the polymer film surface using a soft brush without significantly reducing specular reflectance.

The elemental compositions of the sand particles were also examined at Cranfield using energy dispersive x-ray analysis on both SFEG and ESEM scanning electron microscopes [5]. Representative compositional data in the form of atomic percentage is shown in Table 1 below, which also includes data from MIL-STD silica for comparison. The data shows that the composition of the PSA and Saharan sands are similar, despite the differences in particle sizes. Both sands contain metallic impurities in addition to pure silica. The Arizona sand is purer in composition, in addition to being a finer and smaller particulate material. The presence of calcium in all three sands is usually an indicator of calcite-rich limestone which is commonly found near roads. However, the calcium may have combined with potassium and sodium in the Saharan and PSA sands to form feldspars, the most common mineral in the earth's crust. Both the Sahara and PSA sands contain traces of aluminium, potassium, iron and sodium. This suggests that dust particles of mica are present; which can be found in igneous, metamorphic, and sedimentary rocks. The origin of the carbon, found only in the Arizona sand, is less certain. Arizona has significant coal seams, is also a source of obsidian, and has organic impregnated clays; but the exact origin is speculation. As seen in Fig. 5 (centre) the Arizona sand is notably red in colour, the Saharan sand is notably yellow, and the PSA sand is dark brown or black.

TABLE 1. Elemental composition of sands used, with MIL-STD silica for comparison

Sand type	C	O	Na	Mg	Al	Si	Cl	K	Ca	Ti	Fe	Total
atomic % (SFEG)												
Sahara		65.56	0.55	2.16	5.46	22.57	0.59	1.16	0.29	0.09	1.57	100
Sahara		62.86	0.41	1.49	6.81	24.36	0.53	2.01	0.38		1.15	100
Sahara		65.54	0.74	2.74	7.95	17.44	0.81	1.63	1.31	0.14	1.69	100
Sahara		76.61	0.45	1.63	3.5	6.04	0.37	0.55	9.84		1.02	100
Sahara		69.23		1.22	2.48	5.69	0.39	0.44	19.77		0.77	100
Sahara		65.65		1.07	4.08	26.82	0.39	1.06	0.26		0.68	100
Arizona	10.41	63.68		2.8	11.08	5.58			4.18		2.27	100
Arizona	6.92	56.66		0.8	16.13	14.32			1.58		3.59	100
Arizona	5.98	64.64		0.86	9.04	17.28			1.18		1.02	100
Arizona	6.39	62.28		0.84	13.72	13.5			1		2.28	100
Arizona	4.4	64.33		0.3	12.28	16.08			0.44		2.18	100
Arizona	5.45	66.9		0.23	5.6	21.17			0.21		0.45	100
PSA	0	58.34	0.54	0.53	8.79	26.01	0.36	2.01	1.43		1.98	100
PSA		63.93	3.75	0.55	14.35	14.9	0.17	0.6	0.25		1.5	100
PSA		49.32			14.93	21.9	0.67	10.64			2.54	100
PSA		46.54	0.91	0.76	18.32	21.82		5.67	1.24		4.74	100
PSA		59.18		0.97	12.47	19.83	0.47	3.24	0.59		3.26	100
MIL-STD silica		64.41			0.93	34.18					0.48	100
MIL-STD silica		67.81			1.35	30.84						100
MIL-STD silica	7.09	59.5			0.33	32.92	0.16					100
MIL-STD silica		70.71			5.62	19.23	0.11	4.14			0.2	100
MIL-STD silica		66.92			0.19	32.62	0.16					100
MIL-STD silica		63.34			0.31	36.2	0.14					100

In addition to assessing the optical properties of the polymer film before and after the cleaning experiments, the reflecting surfaces were examined by visual microscopy. A selection of these images is presented below in Figures 9-11 which show the polymer film sample surfaces after having been soiled with the three sand samples and after cleaning with the range of brushes in the presence of water. For example in Fig. 9 we can see the scratches caused when the polymer reflector is cleaned with the hard brush, as demonstrated optically in Figure 6 earlier.

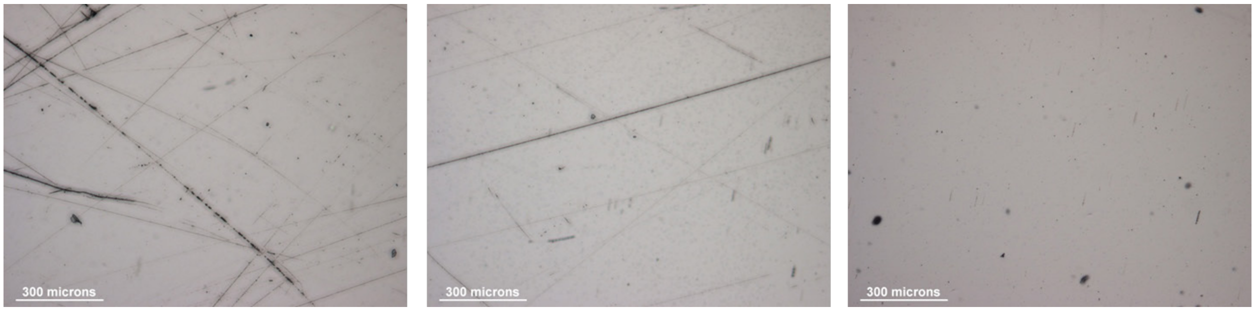

FIGURE 9. Polymer film surface cleaned with the hard brush, water assisted, soiled with the following sands: (a) Arizona, (b) PSA and (c) Sahara after 400 cycles

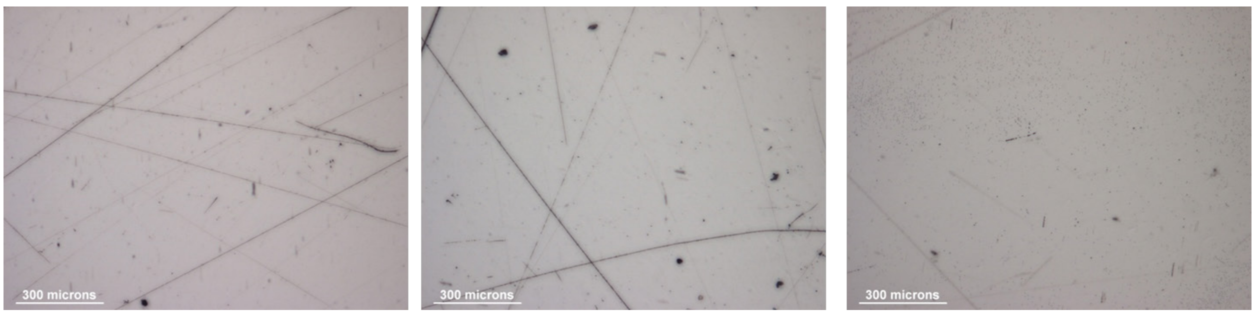

FIGURE 10. Polymer surface cleaned with the medium hard brush, water assisted, soiled with the following sands: (a) Arizona**,** (b) PSA and (c) Sahara after 400 cycles

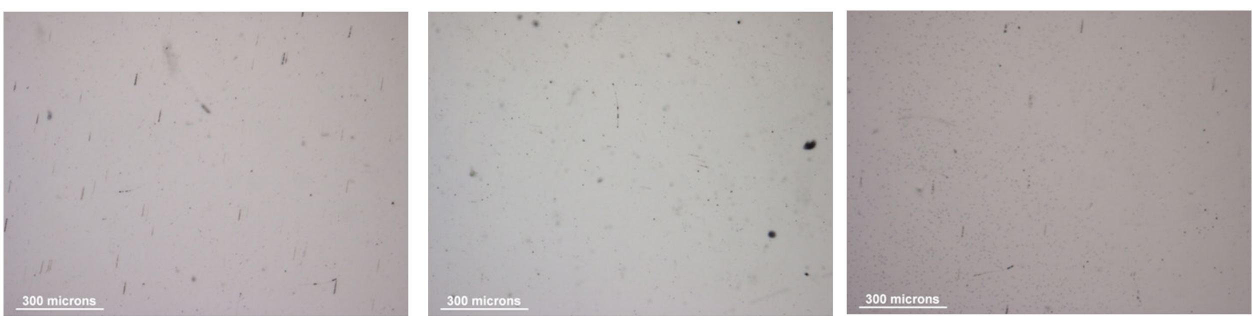

FIGURE 11. Polymer film surface cleaned with the soft brush, water assisted, soiled with the following sands: (a) Arizona**,** (b) PSA and (c) Sahara after 400 cycles

Note that the severe surface damage is not seen in Figure 9(c) with the Saharan sand, which we attribute to the size of the particles. In this case we speculate that the large Saharan sand particles have been swept from the surface during the first cleaning cycle of the hard brush. Figure 10 shows the corresponding result for the medium hardness brush. Figure 10 shows the corresponding result for the medium hardness brush. The surfaces exhibit surface scratches once again, as we might expect from the specular reflectance results. The Saharan sand again produces an anomalous result, with slightly more damage visible using the medium brush than using the hard brush. As before, we believe this may be a characteristic of the large particle size. For the medium hardness brush, it may be that a small number of Saharan sand particles remain on the surface to cause a few small scratches. The final set of images represents the soft brush cleaning, and is shown in Fig. 11. For the soft brush cleaning, it is clear that no scratching of the surface has occurred during particle removal. The only features visible on the surface of the film are a small number of dust particles and the occasional water stain. Again, the result backs up the specular reflectance measurements of Fig. 6.

CONCLUSIONS

This research work demonstrates that it is possible to contact clean polymer film reflectors by using a soft brush in the presence of water. Under such a regime the specular reflectance of the film is maintained and there is no visible damage to the surface layer of the film. The polymer film was tested under accelerated aging conditions when soiled with sand particles from three locations, using sand and dust samples that cover a range of particle sizes, shapes, hardness, and elemental compositions. The soft brush cleaning process, with water, produced good results in all cases. Reflectance measurements were carried out at both Cranfield University in the UK and at the PSA in Spain, using different reflectometers, in order to further validate the results of the cleaning experiments.

Future work will include the removal of dust and sand particles from outdoor collectors at the PSA using brushes covering a range of bristle hardness, and also investigating the contact cleaning of reflecting surfaces other than polymer film.

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