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Research Article

Rugometric and Microtopographic Inspection of $Cr–Cr_2O_3$ Cermet Solar Absorbers

Manuel F. M. Costa and V. Teixeira

Departamento de Física, Universidade do Minho, 4710-057 Braga, Portugal

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The development of new efficient and cost effective solar energy collectors and converters either quantum or thermal attracts great attention and effort in a number of research laboratories all over the world. $Cr–Cr_2O_3$ cermet PVD coatings can be successfully employed in thermal converters. Their energy conversion efficiency depends on their chemical and physical structural characteristics and related optical properties like reflectance, emittance, solar light absorption, or absorptance and transmittance. Parameters such as roughness and topographic characteristics of the produced coatings will greatly influence their relevant optical properties. A careful evaluation of the coatings' roughness and their microtopographic inspection is fundamental. The $Cr–Cr_2O_3$ cermet coatings sputter deposited on cooper and aluminium shows similar absorption (92%) but the first ones present a better emittance and higher waviness (over 30%) with similar roughness. In comparison with commercially available solar panels with a slightly better absorption but worse emittance our coatings have a much lower waviness (~150%) and roughly 50% higher roughness.

1. INTRODUCTION

The Portuguese weather is adequate for the use of solar collectors for water heating. Presently most of the thermal collectors are manufactured with absorber surfaces produced by conventional techniques without the best optical properties adapted to our conditions. The light levels absorption is good enough for our weather but surface emittance is not [1–3]. Spectrally selective surface coatings for absorbers in high performance solar collectors and electrochromic devices for modulation solar transmittance in "smart buildings" can be produced with increasing success by different processes [1–8] from many years. Magnetron sputtering is such a technique widely used in thin film production [3–5, 8–11]. This physical vapour deposition process is a cleaner process compared to conventional techniques to produce black paintings (chemical processes) or selective surfaces such as black chrome (by electrodeposition), with pollutant solvents, dangerous solutions, and environmental impact of the solid waste and water residuals. The advantages of the PVD technique, being an atomistic process under vacuum, allow the deposition of thin (dense or porous) graded or multilayer coatings with controllable level of defects, good adherence, and controllable residual stress [1, 3, 9]. For the deposition of layered oxide or nitride coatings with a gradient in composition (such as $Cr-Cr_2O_3$ cermet selective absorber coating) it is possible to control, at an atomic level, the addition of these elements to the ceramic matrix. Thus we achieve an improved uniformity of the crystalline phases and metallic constituents presented in the composite coating system. The work that is being done at the University of Minho envisages a coherent study of sputter deposited metal oxide and nitride thin multilayered and graded coatings for solar energy applications. Coatings for both static and dynamic control of radiative heat transfer through absorbing surfaces are optically characterised. As metal base in static solar selective coatings, semitransparent nitrides and oxides of Ti, ZrN, and Al films doped with transition metals (W or Mo) are investigated. Tungsten, titanium, and zirconium oxides over layers of a photovoltaic material are also studied to be used in transparent electrochromic devices capable of automatic modulation of solar transmittance. The influence of preparation conditions on the microstructure and on the solar selective properties of these oxides and layered coatings is investigated [1, 3]. A large array of characterisation techniques of surface and interface analysis using advanced surface analysis

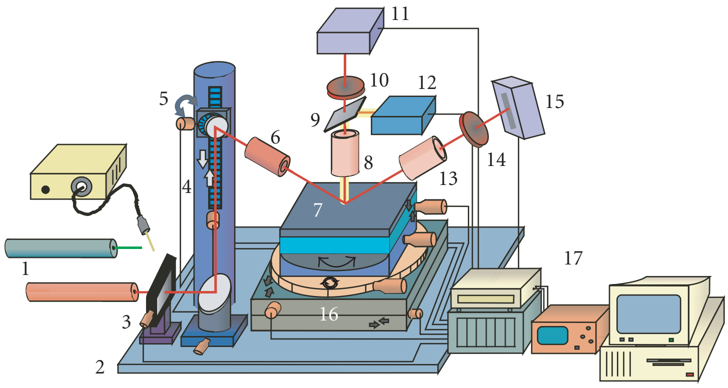

Figure 1

systems (including XPS, AES, XRD, SEM; TEM, AFM, STM, UPS) is employed [1, 4, 9, 10, 12]. Further, we introduce the issue of roughness measurement and microtopographic evaluation of coatings's final materials as a quality nondestructive evaluation [1]. We will briefly describe the methods and system employed in the relief evaluation process. Results of the topographic inspection of our graded $Cr-Cr_2O_3$ cermet's samples on aluminium and copper bases, in comparison with one commercial thermal collector, are presented and discussed.

2. EXPERIMENTAL

In order to perform the roughness and micro-topographic inspection of our $Cr-Cr_2O_3$ cermet solar absorbers we used the system developed by the first author at the Physics Department of the Universidade do Minho. The latest version of our microtopographers [11, 13, 14] is the MICROTOP.06.MFC system and is briefly described below. The system is based on an active optical triangulation method with oblique incidence and normal and, or, specular observation, and mechanical sample's scanning. The surface to be inspected is scanned by an oblique light beam. A small, diffraction limited, bright spot is projected onto the sample. The bright spot is perpendicularly imaged onto electronic photosensitive detection systems in order to assess its lateral position. The area of the surface to be inspected is scanned point by point by the "sensor's tip" (the light beam focused onto the surface). In order to overcome the triangulation's inherent problem of shadowing and mutual reflection we scan the sample consecutively with two opposite angles. The results are then matched and the final set of three-dimensional coordinates is obtained. The reproduction of surface's relief structure can then be performed in different ways and statistical surface characterization parameters are computed. The MICROTOP.06.MFC sketched on Figure 1 is a robust and versatile system specially designed to accurately perform the micro-topographic inspection of the rough surface of small samples. It allows the inspection of a large variety of surfaces with resolutions that can be driven down to the submicron level with dynamic ranges up to 1 : 5000. It was used in different inspection tasks such as thickness measures and relief mapping of a series of thin coatings including thin sputtered cooper, tin dioxide and silver films, polyethylene films, several kinds of fabrics (to the author knowledge for the first time in a noninvasive way), evaluation of the dependence of the pasting quality on the roughness of thermoplastic rubber soles, roughness measure, and integral topographic inspection of polyethylene moulds, graphite samples, wax casts, paper samples [1, 10, 11, 13, 14]. An oblique light beam (two HeNe lasers at 632.8 nm and 534 nm, and one Xenon white light source are available and can be easily interchanged) shines on the surface placed on a scanning assembly. A rotation stage placed on a vertical stand is used to mount the laser allowing easy change of the incidence angle. In order to guide the incident beam onto the sample an incidence optical system was assembled. It comprises a neutral density filter for optical power control and a lens system that cleans and focuses the beam onto a diffraction limited spot on the surface. The sample positioning set-up is formed by an X, Y precision linear stage moved by two step motors allowing the sampling of points on a rectangular array separated by distances down to 1.25 μm. In order to resolve shaded areas and mutual reflections, a high precision rotational stage is used allowing easy change to opposite light incidence. It can also be used to help the sample positioning. In order to keep the incidence and reception optical systems in accurate focus over the sample, the X, Y scanning system rests on a vertical movement precision stage endowed of computer controlled motion provided by a reliable accurate DC encoder with high positioning repeatability and resolution. The observation optical system is formed by one of different microscope objectives chosen according to the characteristics of the surface's relief. It will be used to image the light spot onto the optoelectronic photo-sensitive detection system(s). CCD line-scan cameras are commonly used. However, position sensitive devices (PSDs) or differential detectors can be used instead or simultaneously. The use of the CCD array adds the extra advantage of confocality due to the small size of the photo-elements. The introduction of a 2D CCD camera for visual inspection of the samples allows an easier sample positioning. A personal microcomputer acquires the data

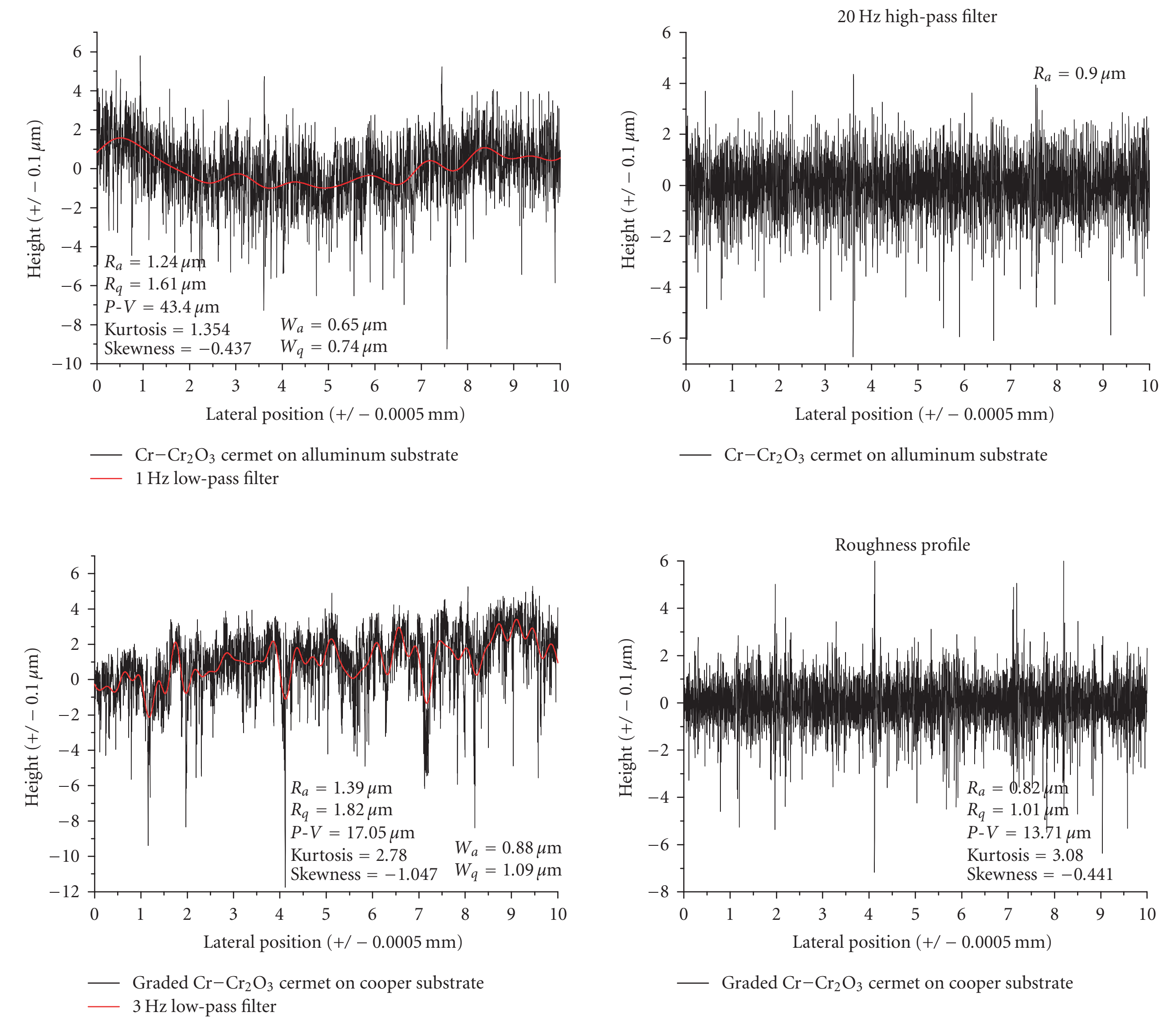

Figure 2

and takes control of the whole inspection process and result's presentation. The calibration procedure is a major issue in this technique as it might take care of some misalignment or aberration problems. It can be efficaciously done simply by moving vertically a reference sample while registering the lateral spot's position.

3. RESULTS AND DISCUSSION

As previously mentioned in the introduction we inspect topographically the $Cr{-}Cr_2O_3$ cermet solar absorbers produced in our lab aiming to achieve the best performance. Two systems were employed: our noninvasive inspection system, briefly described above, and the well-known commercially available Rodenstock RM100 profilometer. Both systems allow in-depth resolutions in the micron and submicron ranges. The coatings to be inspected are typically tens of microns to a few microns thick and smooth with roughness lower than the substrate they are deposited on. Nevertheless, and in fact, what really matters is the whole system substrate/coating that has a particular topographic structure that our micro-topographers can efficaciously evaluate. In this communication we will not perform an analysis of the influence of the solar panels surface's roughness or relief structure on the energy conversion efficiency. In the following paragraphs we just present a few results of the profilometric and micro-topographic inspection on two graded $Cr{-}Cr_2O_3$ cermet films deposited over aluminium and cooper substrates and one commercially available solar panel. All results presented here were obtained with the MICROTOP.03.MFC. However, the statistical parameters obtained on the inspection of these samples are in good agreement with the results obtained with the Rodenstock RM100 profilometer with differences smaller than 0.17%. Both $Cr{-}Cr_2O_3$ cermet films

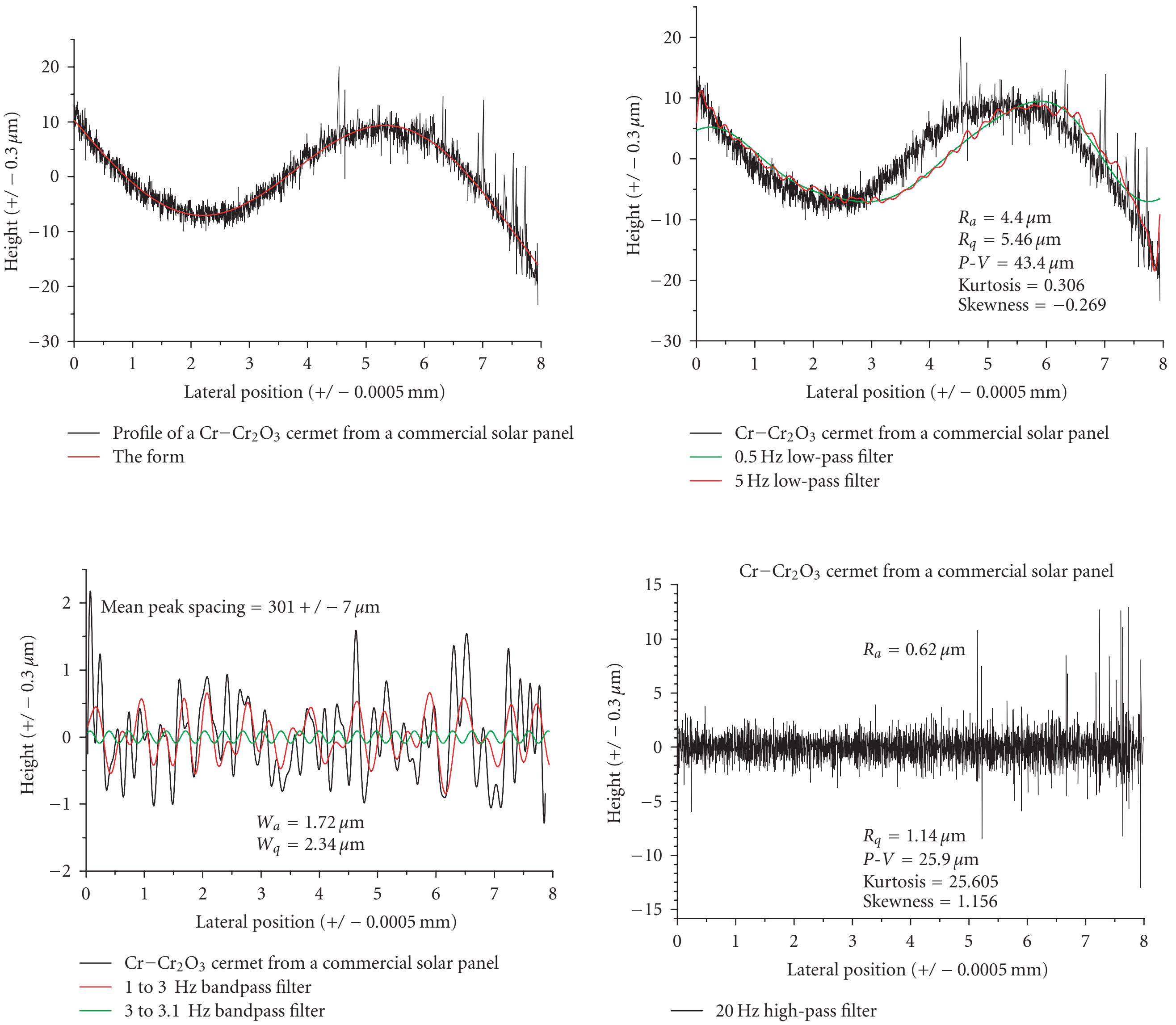

FIGURE 3

were deposited in a SCM-650 Alcatel sputtering system on a substrate (aluminium or cooper) at 60 mm distance from the target and at a temperature of 150°C. Ten layers were deposited switching on and off the O_2 flux for controlled time intervals. Both films have good adherence. The films have a similar efficiency of energy conversion with roughly the same absorption (92%) and a 15% better emittance in the case of the film on cooper substrate (0.087 and 0.10). The efficiency of our films matched with typical commercially available solar panels (Figure 3) is slightly worse in terms of absorption but significantly better in what concerns the emittance (0.15 to ∼0.06). On Figure 2 we present two profiles of two $Cr-Cr_2O_3$ cermet solar absorbers; the first on an aluminium substrate and the later on cooper. The waviness and roughness regimes are separated and some typical ISO's standards statistical parameters [12] (the mean roughness R_a and waviness W_a, the root mean square roughness R_q and waviness W_q, the peak-to-valley, the skewness and kurtosis of the profile functions, and the mean peak spacing) are calculated. The roughness regimes of both films do not differ significantly but the waviness of the films on the cooper substrate is 30% higher (0.65 to 0.88). Its recorded emittance is also slightly higher (∼15%).

On the next set of images we present a few results of the inspection (profilometric and topographic) of a $Cr-Cr_2O_3$ cermet solar absorbers from a commercially available solar panel. On Figure 3 one profile of a 10 mm line sampled on 4041 points is presented. The "error" of form is marked and then removed from the profile. The waviness profile is presented. Low-pass FFT filtering with different cut-off frequencies was applied in order to help the analysis [15]. The spatial wavelength, roughly 300 microns, is relatively large. The roughness of this film is just around 50% of the roughness of our films but its waviness is much higher (∼150%).

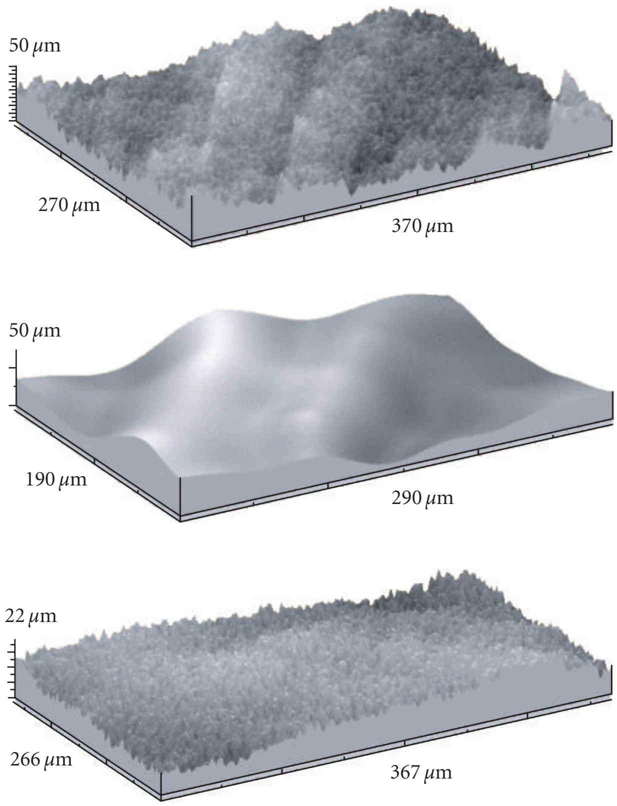

Figure 4

The efficiency of our samples is higher than this commercial product. In fact the commercial panel presents a solar absorbance of 94% while this value for our films is of 92%, but the emittance of our films is significantly better (87% and 0.06 to 0.15).

The last graphs in Figure 4 show some results of the microtopographic inspection of a small portion, $270 \times 370\,\mu m^2$, of the panel. On the top, the microtopographic relief map is shown after form removal. The separation of the waviness and roughness structures is also needed and is very useful in analysing operational aspects. These structures are presented in the two lower graphs, respectively.

4. CONCLUSION

The importance of environmentally safe energy production or conversion systems is growing every day. Composite $Cr-Cr_2O_3$ cermet coatings produced by PVD present excellent controllable characteristics for solar energy to heat conversion. Furthermore, graded coatings can be used in spectrally selective surfaces for thermal collectors and energy-efficient windows. The full characterisation and control of the coatings characteristics are of utmost importance. Among those characteristics are the ones related to the coating's surface relief. Our work is proving the significance and importance of the profilometric and integral microtopographic inspection of the kind of valuable products. The interest of the employment of an inspection system such as our MICROTOP.06.MFC on these inspection tasks was demonstrated. Although no final conclusions of the overall research project can be drawn, yet from the results of this work a few remarks can be pointed out. NDE techniques such as the employed roughness and micro-topographic optical inspection are of crucial importance as method of process and quality control to obtain spectrally selective surfaces with more reliable high-performance properties. Our $Cr-Cr_2O_3$ cermet coatings deposited on cooper and aluminium have similar absorption (92%) but the first ones have a slightly better emittance ($\alpha = 0.87$ and $\varepsilon = 0.06$) and higher waviness ($\sim$30%) but similar roughness. In comparison with a commercially available solar panel with a much higher waviness ($\sim$150%) but smaller roughness ($\sim$50%), our films have a slightly worse solar absorption but significantly better emittance.

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