A study of sol gel process parameters on CoCuMnO\textsubscript{x} selective coating characteristics

Fatma Taha, Nahed El Mahallawy and Madiha Shoieb 1

1 Design and Production Engineering Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt
2 Surface Protection and Corrosion Control Department, Central Metallurgical Research and Development Institute (CMRDI), At Tebin, Helwan, Cairo, Egypt
E-mail: fatma.taha35@yahoo.com

Abstract
This research addresses the effect of process parameters on the optical properties of solar selective coating. The proposed study discusses the deposition of a selective coating of CoCuMnO\textsubscript{x} onto stainless-steel substrate. The coating was prepared via a sol-gel route and dip coating process. Mechanical adhesion between the coating and the substrate was increased through increasing the surface roughness of the substrate. Four parameters were discussed; precursor concentration, withdrawal rate, number of coating layers and the heat treatment temperature. The best achieved absorptivity was 0.906 in the wavelength range of (200–900 nm) and emissivity 0.116 in the wavelength range of (2.5–25 \( \mu \)m) for a sample with precursor molar ratio divided by 60, 1.5 cm min \(^{-1} \) withdrawal rate, double coating layer and 450 °C heat treatment temperature. Detailed coating characterization was discussed through XRD, EDX and SEM analysis.

1. Introduction

In the last decade, a lot of scientific research concerned with solar selective coatings have been released due to the awareness of solar energy exploitation as a free and renewable energy resource. Selective coatings are characterized by having high solar absorptivity (\( \alpha \)) in the UV range and low thermal emissivity (\( \varepsilon \)) in the IR range. Solar selectivity is measured by attaining the ratio of absorptivity to emissivity (\( \alpha / \varepsilon \)). However, a more indicative measurement was proposed by [1] which gives more weight to the absorptivity relative to its importance in the form of \( \alpha - 0.5 \varepsilon \). Selective coating can be used for domestic applications such as space heating and water heating. Moreover, other applications involve water evaporation, water desalination and electricity generation.

Ternary spinel-like oxides such as CuFeMnO\textsubscript{4}, CoCuMnO\textsubscript{x} and CuCr\textsubscript{2}O\textsubscript{4} are widely used as solar selective coatings [2]. CuFeMnO\textsubscript{4} was used by Shi et al as a photo-thermal coating layer on a cordierite honeycomb ceramic substrate to increase the water evaporation rate for the sake of producing clean water. The prepared sample succeeded to attain 98.2% solar absorptance under the effect of the solar simulator with an intensity of 1000 W m\(^{-2} \) (AM 1.5) [3]. CoCuMnO\textsubscript{4} has also shown superior selective characteristics as shown by Vince et al [4]. The coating was deposited over an aluminum substrate and achieved a spectral selectivity \( \alpha / \varepsilon \) of 0.95/0.04. The effect of the substrate material was investigated by deposition of CoCuMnO\textsubscript{4} on copper and aluminum substrates [5] and the results indicated that the substrate material affects the optical properties especially the emissivity (\( \alpha = 0.9, \varepsilon = 0.011 \) for copper and \( \alpha = 0.9, \varepsilon = 0.029 \) for aluminum substrates). Furthermore, Ma et al [6] tested CoCuMnO\textsubscript{4} to be used as solar absorber in flat plate solar collectors. The coating was applied on stainless steel substrates and achieved \( \alpha = 0.88 \) and \( \varepsilon = 0.12 \). Kim et al [7] worked on enhancing the efficiency of concentrated solar powers (CSPs) by spray-coating a two-layer tandem structure of (CuFeMnO\textsubscript{4}/CuCr\textsubscript{2}O\textsubscript{4}) onto Inconel 625 substrates and achieved 90.3% solar to thermal conversion efficiency.

All the previously mentioned efforts in the production of cermet solar selective coatings were prepared through sol-gel approach. This technique converts the solution ‘Sol’ which usually contains a mixture of metal
oxides and solvents into a ‘Gel’ by the means of poly-condensation of the molecules to form a macromolecular network structure [8]. Different preparation parameters are involved in the nature of the developed jet. For instance, the composition of the starting solution controls the formation of gel shape which can turn into bulk, fiber, or coating film [9]. The type of deposition technique is governed by several constraints like the thickness of the coating layer, the adhesion, the shape and type of substrate, etc. Dip and spray coatings are the commonly used coating methods in sol-gel coating technique, however, spin coating, laminar flow coating and printing are also used [10–15]. Controlling sol-gel process parameters has a great role in obtaining enhanced properties for the desired application. For example, Kumaresavanji et al [16] studied precursor molar concentration, viscosity and pH values as effective parameters on structural and magnetic properties of ferromagnetic La2/3Ca1/3MnO3 nanotubes. Moreover, Nguyen et al [17] succeeded in applying Anatase-Titania on χ-alumina fibers through sol-gel dip coating. The direct effect of several process parameters such as molar ratio of the precursors in TiO2-sols, dip-coating time, drying duration in air, heating processes and number of cyclical repetitions of the process on the structural and morphological characteristics of the coating was found.

In this work, the CoCuMnOx spinel ceramic film was applied onto stainless steel 304 substrate. Stainless steel (SAE 304) is considered the best-known austenitic grade of stainless steel. It has distinctive characteristics represented in forming and welding properties, plus the corrosion/oxidation resistance which makes it an excellent substrate for high temperature solar absorber application. The coating precursor was prepared and deposited through sol-gel dip coating method. The effect of process parameters such as precursor concentration, withdrawal rate of dipping, number of coating layers and heat treatment temperature on optical properties was studied.

2. Experimental work

The experimental work is held through four steps which are Base metal pre-processing, Sol-gel preparation, dip coating and samples post-processing. These steps are discussed in the next subsections in details.

2.1. Base metal pre-processing

Prior to dip-coating, substrate material has to be specially prepared in order to maintain acceptable adhesion of the coating to the base metal. At first, stainless steel samples of 1.5 mm thickness were cut into strips of 3 × 10 cm. Then, surface roughness of the samples was increased to 1.53 μm by sand blasting. This ensures enhanced mechanical adhesion between the coating and the substrate. Surface roughness was measured by Time TR110 surface roughness tester. Last step involved ultrasonic cleaning of the samples by immersing them into acetone and sonicating them in ISOLAB ultrasonic bath for 10 min to ensure the removal of any grease or sand residue. Samples were then dried by hot air and kept in a vacuum container ready for the coating process.

2.2. Solution preparation

The procedure of preparation of sol-gel coating of CoCuMnOx was previously discussed and shown in details in several previous research [4, 5, 18]. The main precursor of the solution is based on three main metal oxides; Co II acetate, Cu II nitrate and Mn II acetate. Solvents used were ethylene glycol and absolute ethanol. Four different coatings with different concentrations were prepared by dividing the molar ratios of metal oxides by 50, 60, 70 and 80 respectively.

2.3. Dip-coating process

Prior to dip-coating, the gel needed to be re-agitated at proper speed at about 50 °C, to maintain its dense viscous form before dipping. As the coating thickness can result in different optical properties, this thickness was varied by changing the withdrawal rates or increasing the number of coating layers. Accordingly, three different withdrawal rates were used in this experiment; 0.5, 1 and 1.5 cm min⁻¹. In addition, single-layered or double-layered coatings were also investigated. Intermediate heat treatment was applied on the first layer before the deposition of a new one. This was emphasized in [4] where it was stated that applying the subsequent coatings while the coating was still wet prevents the next coating layer from equally spreading over the whole substrate surface.

2.4. Heat treatment

After withdrawing the samples from the solution, they were held in a vertical position then inserted into a muffle furnace for heat treatment at 450 °C for 30 min. Figure 1 shows the samples just after the dip coating process and ready for the heat treatment step, and a final sample after heat treatment. Other samples were heated at 700 °C for 30 min. It is worthy to mention that the coating after heat treatment showed a homogeneous coating layer and a sufficient adhesion.
3. Characterization and testing

The optical properties including absorptivity and emissivity were measured at three different spots of the coating area for each sample. Then the average value was obtained for two samples. Absorptivity ($\alpha$) was measured using T90 + UV/VIS spectrometer PG instruments limited (scan range: 0.2–0.9 $\mu$m), while Emissivity ($\varepsilon$) was measured by Thermo Finnigan FT-IR spectrometer Nicolet 380 (scan range: 2.5–25 $\mu$m).

Absorptivity was calculated through the following equation:

$$\alpha = \frac{\int_{\lambda_1}^{\lambda_2} (I_0(\lambda) \cdot (1 - R(\lambda))) d\lambda}{\int_{\lambda_1}^{\lambda_2} I_0(\lambda) d\lambda}$$

where:
- $R$ is the reflectance obtained by the UV/VIS spectrometer in the entire scan wavelength range
- $I_0(\lambda)$ is the spectral power density of the solar radiation air mass 1.5
- $\lambda_1, \lambda_2$ are the limits of the wavelength range

On the other hand, emissivity was calculated through the following equation:

$$\varepsilon = \frac{\int_{\lambda_1}^{\lambda_2} (P(\lambda) \cdot (1 - R(\lambda))) d\lambda}{\int_{\lambda_1}^{\lambda_2} P(\lambda) d\lambda}$$

where:
- $R$ is the reflectance obtained experimentally from FTIR in the entire scan wavelength range.
- $P(\lambda)$ is the spectral radiance of a black body at a temperature 100 °C coherent with the medium temperature applications.
- $\lambda_1, \lambda_2$ are the limits of the wavelength range

Selectivity factor was obtained using the formula ($\alpha - 0.5 \cdot \varepsilon$) [1] which could be derived from the following equation:

$$q_{(net, rad)} = \alpha G_{\text{solar}} + \varepsilon \sigma (T_{sky}^4 - T_e^4)$$

Coating thickness was determined by taking a section of the coated samples and measuring it through optical microscopic images obtained by OPTIKA B-500-MET optical microscope. A number of points was taken along the section and the average value was determined.

Existing phases in the coating were determined by XRD using Bruker d8 Advance. SEM-EDX investigation for some samples of interest was also made using FEI-INSPECT S50 device.
4. Results and discussion

4.1. Effect of different precursor concentrations on the optical properties of CoCuMnOx coated stainless steel

Under same conditions, the effect of changing the coating composition on the absorptivity of the coating was discussed in details. Four different precursor molar ratios (MR/50, MR/60, MR/70 and MR/80) were studied.

Figure 2(a) shows the effect of changing precursor molar ratio on the absorptivity for different numbers of coating layers and different withdrawal rates. It was observed that the decrease in the precursor concentration increased the absorptivity in most cases for a single coating layer. The increase range was between 1%–2%, depending on the withdrawal rate. As for the double coating layer, increasing the precursor concentration
increased the absorptivity. This matches with the emphasis of Zheng et al.\cite{22} where they stated that the increase in solar absorption is related to the increase in precursor concentration for the enhanced thickness cases.

As for the emissivity, figure 2(b) shows the effect of changing the precursor molar ratio on the absorptivity for different numbers of coating layers and withdrawal rates. It was observed that there was no significant difference in the emissivity values in most cases. Most of emissivity values were between 0.12 and 0.15.

Due to the slight differences in emissivity values that were found in most cases, the selectivity was significantly affected by the change in the absorptivity. Therefore, the calculated selectivity shown in figure 2(c) had the same trend of the absorptivity that was discussed earlier. Best results for absorptivity, emissivity and selectivity were attained by the precursor concentration of MR/60.

4.2. Effect of withdrawal rate on the optical properties of CoCuMnOx coated stainless steel

The withdrawal rate is one of the parameters that determines the thickness of the coating and accordingly, the optical properties. Figure 2(a) shows the effect of changing withdrawal rates on the absorptivity of different coatings. In case of single coating layer, it was observed that there was no significant change in the absorptivity with the increase of withdrawal rate in all concentrations proposed. As for the double coating layer, the absorptivity values tended to increase with increasing the withdrawal rate from 0.5 cm min\(^{-1}\) to 1.5 cm min\(^{-1}\). This increase was about 1% for MR/50, 3% for MR/60, 2% for MR/70 and 1% for MR/80.

The relation between emissivity and withdrawal rate is shown in figure 2(b). The emissivity in the case of single coating layer tended to increase from 0.24 to 0.31 for the precursor concentration (MR/50) as the
Figure 4. (a) The relation between the thickness of the coating and absorptivity. (b) the relation between the thickness of the coating and Emissivity. (c) the relation between the thickness of the coating and selectivity.

Table 1. The crystal size of the coating of some chosen samples and the corresponding selectivity to each one of them.

| Case number | Concentration | Withdrawal rate | No. of layers | Heating temp. | Avg. Crystal Size (nm) | \( \alpha \) | \( \varepsilon \) | Selectivity |
|-------------|---------------|-----------------|---------------|---------------|------------------------|--------|--------|-------------|
| Case 1      | MR/60         | 1.5 cm min\(^{-1}\) | 2             | 450 ℃        | 38                     | 0.906  | 0.116  | 0.85        |
| Case 2      | MR/60         | 1 cm min\(^{-1}\)  | 1             | 450 ℃        | 41.07                  | 0.878  | 0.193  | 0.78        |
| Case 3      | MR/60         | 1 cm min\(^{-1}\)  | 1             | 700 ℃        | 77.53                  | 0.923  | 0.161  | 0.84        |
| Case 4      | MR/80         | 1 cm min\(^{-1}\)  | 1             | 450 ℃        | 33.4                   | 0.891  | 0.137  | 0.82        |
| Case 5      | MR/80         | 1 cm min\(^{-1}\)  | 1             | 700 ℃        | 54.23                  | 0.871  | 0.157  | 0.79        |
withdrawal rate increased from 0.5 to 1.0 cm min\(^{-1}\) then tended to decrease to 0.15 by increasing the withdrawal rate to 1.5 cm min\(^{-1}\). The change in emissivity was more pronounced for the highest concentration (MR/50) and decreased gradually with decreasing the concentration until almost no change was reached for (MR/80). In the cases of double coating layer, there was no significant change in emissivity values.

Selectivity values in return changed by 1% to 3% with increasing the withdrawal rate in most cases as it is shown in figure 2(c). The best result of absorptivity, emissivity and selectivity were reported for the withdrawal rate of 1.5 cm min\(^{-1}\). Sánchez et al [23] discussed the effect of withdrawal rate on optical properties and found a strong relation between the withdrawal rate and the coating thickness which subsequently affected the optical properties. Similar investigations were also reported in [18].

4.3. Effect of number of applied coating layers on the optical properties of coated stainless steel
The absorptivity values increased when a second layer of coating was added in the concentrations of MR/50 and MR/60. However, the concentration of MR/70 and MR/80 behaved in an opposite way as shown in figure 2(a). The biggest change in absorptivity was in the case of precursor concentration (MR/60) and 1.5 cm min\(^{-1}\) withdrawal rate. The absorptivity in this case increased by 4% when a second coating layer was added.

As for the emissivity, shown in figure 2(b), it was observed that the emissivity values tended to decrease slightly in most of the cases when a second coating layer was added.

Combining absorptivity and emissivity values together, an increase in selectivity values in (MR/50) and (MR/60) concentrations was found. On the contrary, decreasing selectivity was observed in (MR/70) and (MR/80) as shown in figure 2(c). The best absorptivity, emissivity and selectivity results were 0.906, 0.116 and 0.85 respectively and they were attained by the double coating layer.

4.4. Effect of heat treatment on the optical properties of coated stainless steel
Raising the heat treatment temperatures can result in enhancing optical properties. Therefore, the present samples were heated at 450 °C and at 700 °C. It was found that the absorptivity increased by 5% for (MR/60) when the temperature increased from 450 °C to 700 °C. This was previously found in [22] where it was stated that absorptivity increased with the temperature increase. However, the molar concentration has to be taken into consideration as the effect of raising the heat treatment temperature was not efficient and declined in case of (MR/70) concentration and even a reduction in absorptivity at (MR/80) was found when heated at 700 °C where the absorptivity decreased by 2%. This emphasizes the important role of precursor concentration on the optical properties. Detailed results are illustrated in figure 3(a).

As for the emissivity, figure 3(b), the values dropped by 3% in case of (MR/60) when the heat treatment temperature increased from 450 °C to 700 °C. In case of (MR/70), a slight decrease in emissivity by 0.3% was found while at (MR/80) an increase in emissivity by 2% was obtained. As a result, selectivity values were affected in return.

The overall selectivity was increased by 6% for (MR/60). This meant that optical properties were enhanced in case of heat treatment as previously mentioned in previous research. However, for (MR/70) the selectivity increased by only 1%, while it decreased by 3% for (MR/80). Illustration for these results is shown in figure 3(c).
4.5. Effect of coating layer thickness on optical properties

The term ‘thickness sensitive spectrally selective’ (TSSS) in paint coatings emphasizes the relation between coating thickness and optical properties. This relation was investigated by Ma et al. [24] at different annealing temperatures and the results revealed an increase in coating thickness which resulted in lower selectivity. At 500 °C, for example, the thickness range was between 2.41 and 5.16 μm, and the selectivity decreased by almost 50%.

Figure 4 shows the effect of average thickness on optical properties. As it was mentioned in earlier research, dip coating in sol-gel technique did not result in a precise thickness as it was controlled by a large number of parameters. Therefore, several sample coating thicknesses were measured and the average values were illustrated.

Figure 6. XRD results for stainless steel 304 sample coated using solution of concentration MR/80, withdrawal rate 1 cm min⁻¹, single coating layer and series (a) heated at 450 °C for 30 min, series (b) heated at 700 °C for 30 min.

Figure 7. XRD results for stainless steel 304 sample coated using solution of concentration MR/80, withdrawal rate 1 cm min⁻¹, single coating layer and series (a) heated at 450 °C for 30 min, series (b) heated at 700 °C for 30 min.
Figure 4(a) shows the change of absorptivity average values according to the change in coating thickness. It can be observed that the larger the thickness the lower the absorptivity and the slightly higher emissivity, figure 4(b). Consequently, the selectivity values shown in figure 4(c) show a decreasing trend with increasing the
thickness. It can be concluded that the thinner the coating layer, the better the optical properties obtained. Best selectivity value obtained was 0.85 for a thickness of 4.96 μm.

4.6. Coating characterization [XRD analysis and SEM investigation]

In an attempt to investigate the resulting compounds in each coating, XRD analysis was applied on five samples with different conditions. Table 1 shows the different conditions in each case that will be discussed through this section. Figures 5–7 show the XRD analysis of the five cases. The analysis showed that in all these cases, the following compounds are formed: cobalt copper, copper di-manganese oxide, copper oxide and manganese oxide.

**Case 1.** Shown in table 1 and figure 5, represents the optimum sample that attained the best optical properties. The average crystallite size in this case was 38 nm.

By raising the heat treatment temperature from 450 °C to 700 °C (Case 2 and Case 3 - MR/60), the average crystallite size of the coating compounds apparently increased from 41.07 nm to 77.53 nm with 88.8% relative increase as indicated in figure 6 and table 1. This was accompanied by an increase in absorptivity, decrease in emissivity and significant increase in selectivity from 0.78 to 0.84. The noticeable increase in the average crystallite size can be attributed to the agglomerations of fine particles which in turn led an increase in the quantity of the fine pores that boosted light entrapment and consequently led to absorptivity enhancement as it was emphasized in [6].

As for raising the heat treatment temperature from 450 °C to 700 °C (Case 4 and Case 5 - MR/80), the average crystallite size increased from 33.4 nm to 54.23 nm with 62.4% relative increase as shown in figure 3(c). This was accompanied by a decrease in absorptivity, increase in emissivity and increase in selectivity from 0.82 to 0.79. This indicated that two opposite factors that can affect the optical properties were present: the precursor concentration and heat treatment temperature. The good crystallinity at a higher precursor concentration was previously introduced in [24, 25]. Furthermore, the effect of increasing precursor concentration in enhancing the crystallinity was discussed in [26]. Accordingly, this validates the presented work. As tabulated in table 1, the crystallite size of case 2 which had precursor concentration of (MR/60) was larger than case 4 which had precursor concentration of (MR/80). Likewise, the crystallite size of case 3 was larger than case 5. This meant that decreasing the precursor concentration caused a direct decrease in the crystallite size of the coating compounds.

Figure 8(a) shows SEM image of the sample with the best results of conditions MR/60 precursor concentration, 1.5 cm min⁻¹ withdrawal rate and double coating layer. This case achieved 0.906 absorptivity, 0.116 emissivity and 0.85 selectivity. The shown image illustrates grooves and pores that play an important role in light trapping as discussed earlier. In addition, figure 8(b) illustrates the EDX analysis which shows the elements of the coating (Co, Cu, Mn and O) and the base metal elements (Fe, Ni and Cr).

5. Conclusions

Through this study, CoCuMnO₅ spinel ceramic film was applied onto stainless steel 304 through sol-gel dip coating method and proved to be successful as an effective solar selective coating. Several parameters were discussed that included precursor concentration, withdrawal rate, number of coating layers and heat treatment temperature. Best absorptivity, emissivity and selectivity measurements were 0.906, 0.116 and 0.85, respectively and was considered as the optimum case. The process parameters that resulted in this optimum case were MR/60 precursor concentration, 1.5 cm min⁻¹ withdrawal rate, double coating layer and 450 °C heat treatment temperature. The increase of coating thickness resulted in deterioration of selectivity. The optimum sample with the best optical properties had the smallest coating thickness which was 4.96 μm. Coating characterization proved that the improvement in optical properties was accompanied with an increase in the average crystallite size of the deposited compounds. This work has shown the significance of the tested parameters on the optical properties of solar selective coatings. It also emphasizes the role of the synergy of the different parameters in order to achieve best results.

Acknowledgments

The authors wish to express their sincere thanks to Design and Production Engineering Department and Materials lab in faculty of engineering Ain shams University, Central Metallurgical Research and Development Institute (CMRDI) and Tabbin Institute for Metallurgical Studies (TIMS) for their support during the experimental work.
References

[1] Chen Z, Jain A and Boström T 2014 Simulation of anti-reflection coated carbonaceous spectrally selective absorbers Energy Procedia 58 179–84

[2] Merino M C G, Arreche R, Lassa M S, Lascaleta G E, Estrella A and Rodriguez M E 2015 Combustion synthesis of Co–Cu–Mn oxides deploying different fuels Rev. Mater. 20 779–86

[3] Shi L et al 2019 Multi-functional 3D honeycomb ceramic plate for clean water production by heterogeneous photo-Fenton reaction and solar-driven water evaporation Nano Energy 60 222–30

[4] Vinc J, Šurca Vuk A, Opara Krašovec U, Orel B, Köhl M and Heck M 2003 Solar absorber coatings based on CuCoMnOx spinels prepared via the sol–gel process: structural and optical properties Sol. Energy Mater. Sol. Cells 79 313–30

[5] El Mahallawy N, Shoieb M and Ali Y 2014 Application of CuCoMnOx coat by sol gel technique on aluminum and copper substrates for solar absorber application J. Coatings Technol. Res. 11 979–91

[6] Ma P, Geng Q, Gao X, Zhou T, Yang S and Liu G 2016 Synthesis and characterization of CoCuMnOx spinel ceramic thin films for spectral selectivity absorption RSC Adv. 6 87584–92

[7] Kyung T et al 2016 Copper-alloyed spinel black oxides and tandem-structured solar absorbing layers for high-temperature concentrating solar power systems Sol. Energy 132 257–66

[8] Peterson D S 2014 Sol-Gel Technique (New York: Springer Science + Business Media) (https://doi.org/10.1007/978-3-642-27758-0_1432-2)

[9] Salka S 2013 Sol-Gel Process and Applications Handbook of Advanced Ceramics (Second Edition) (USA: Elsevier Inc.) (https://doi.org/10.1016/B978-0-12-365469-8.00048-4)

[10] Boskerika A, Guebrous L, Chelef H and Benharrat L 2019 Preparation and characterization of bright high quality YAG: Eu3+ thin films grown by sol–gel dip-coating technique Thin Solid Films 683 74–81

[11] Fang M et al 2019 Preparation of highly conductive graphene-coated glass fibers by sol-gel and dip-coating method Journal of Materials Science & Technology 35 1989–1995

[12] Alie C et al 2018 Electrochemical performances of Li2MnO3 films prepared by spray-coated sol-gel reaction J. Power Sources 403 173–83

[13] Yahia A et al 2019 Structural, optical, morphological and electrical properties of indium oxide thin films prepared by sol-gel spin coating process Surfaces and Interfaces 14 158–65

[14] Belleville P F and Floch H G 1994 A new room-temperature deposition technique for optical coatings J. Sol-Gel Sci. Technol. 3 23–9

[15] Chaudhury P, Singh P and Kumar V 2018 Synthesis and characterization of pure ZnO and La-doped ZnO (Zn0.95La0.05O) films via novel sol-gel screen-printing method Optik (Stuttgart). 158 376–81

[16] Kumaresavanji M, Sousa C T, Apolinario A, Lopes A M L and Araujo J P 2015 In situ grown by sol-gel dip-coating method Ceram. Int. 41 158

[17] Nguyen H T et al 2004 Structural and morphological characterization of anatase TiO2 coating on γ-Alumina scale fiber fabricated by sol-gel dip-coating method J. Cryst. Growth 271 245–51

[18] El Mahallawy N, Shoieb M and Eletriby S 2016 Effect of sol-gel process parameters on optical properties of CuCoMnOx selective coat for solar energy applications Journal of American Science 12 41–48 (https://pdfs.semanticscholar.org/b52c/78c2b097a4f5aa2d2e422034a6051929.pdf)

[19] Kumar R, Usmani B and Dixit A 2019 W/SS thin film as high temperature infrared reflector for solar thermal applications: intrinsic properties and impact of residual oxygen Mater. Res. Express 6 106408

[20] Khaled A, El-Mahallawy N, Shoieb M and Atia M R A 2019 PH value variation for effective solar energy harnessing of copper oxide based sol-gel prepared coatings Surf. Topogr.: Metrol. Prop. 7 025006

[21] Cengel Y A and Ghajar A J 2015 Fundamentals of thermal radiation Heat and Mass Transfer: Fundamentals and Applications fifth edition (2 Penn Plaza, New York, NY 10121: McGraw-Hill Education) (http://highered.mheducation.com/sites/0073938187/information_center_view0/index.html)

[22] Zheng Y et al 2017 Effects of precursor concentration and annealing temperature on CH3NH3PbI3 film crystallization and photovoltaic performance J. Phys. Chem. Solids 107 53–61

[23] Encinas-Sánchez V, Macías-García A and Pérez F J 2017 Effect of withdrawal rate on the evolution of optical properties of dip-coated yttria-doped zirconia thin films Ceram. Int. 43 13094–100

[24] Ma P, Geng Q, Gao X, Yang S and Liu G 2016 Solution combustion of spinel CuMnOx ceramic pigments for thickness sensitive spectrally selective (TSSS) paint coatings Ceram. Int. 42 11966–73

[25] Soyla M and Coskun M 2018 Controlling the properties of ZnO thin films by varying precursor concentration J. Alloys Compd. 741 957–68

[26] Popa P L, Crépelière J, Lefort R and Lenoble D 2016 Electrical and optical properties of Cu–Cr–O thin films fabricated by chemical vapour deposition Thin Solid Films 612 194–201