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Characteristics of a solar selective absorber surface subjected to environmental dust in humid air ambient

B.S. Yilbas[a,b,*], H. Ali[b], A. Al-Sharafi[b], N. Al-Aqeeli[b], N. Abu-Dheir[b], F. Al-Sulaiman[a,b], M. Khaled[c]

[a] Department of Mechanical Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
[b] Center of Research Excellence in Renewable Energy, Research Institute, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
[c] Chemistry Department, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

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ABSTRACT

Solar refractory selective absorber surfaces, such as TiN coatings, suffer from dust settlements, which become critically important in terms of the efficient operation of a solar receiver. In the present study, environmental dust characteristics and dust settlement on TiN coating surface are investigated. Water condensation on the dust particles in humid air ambient is simulated while mimicking the actual environmental water condensation. The size distribution of the dust particles is analyzed and the geometric features of the particles are assessed via introducing the shape factor and the aspect ratio. The tangential force required removing the dust particles and dry mud, which is formed from the dust particles and water condensate, from TiN coating surface is measured incorporating the micro-tribometer. It is found that the dust particles have various shapes and the sizes with the average size of the dust particles in the order of 1.2 µm. Dust particles compose of various elements including alkaline and alkaline earth metals. The dissolution of alkaline and alkaline earth metal compounds in water condensate results in a liquid solution, which flows towards the coating surface under the gravitational force. The liquid solution does not form a continuous film at the interface of the dust particles and the coating surface because of the spreading coefficient. The liquid solution increases the tangential force required to remove the dry mud from the coating surface once it dries out.

1. Introduction

Titanium nitride (TiN) coating finds wide applications in industry because of its superior resistance towards corrosion and wear. Titanium nitride (TiN) coated surfaces are also proposed as a solar selective absorber for high temperature air-stable solar receivers [1]. High temperature air-stable solar selective absorbers, in general, operate in air ambient with temperatures over 400 °C to provide cost effective energy harvesting and efficiency improvement in solar thermal power plant and solar cooling applications [2]. However, research towards utilization of air-stable solar thermal selective surfaces is in progress, particularly for high-temperature applications [3]. On the other hand, recent environmental dust storms, particularly in the Middle East, influence significantly on the performance of solar energy harvesting devices because of dust settlement on the device active surfaces [4]. The dust particles have different sizes and shapes and compose of various elements including alkaline and earth alkaline metals such as Na, K, and Ca [5]. In humid air ambient, where water condensates onto the dust particles, an extra effort is required removing the dust particles from the surfaces. Alkaline and earth alkaline compounds in the dust particles dissolve in water condensate and form a chemically active solution. The liquid solution flows towards the surface under the gravity where the dust particles are settled and it forms a liquid interlayer between the surface and the dust particles with progressing time. Once the liquid solution dries out, the adhesion between the surface and the dust particles increases significantly because of the dried interlayer solution [6]. In general, adhesion between the dried solution and the surface is governed by the surface free energy of the substrate material and interfacial energy between the dried solution and the solid surface. The efforts required to remove the dust particles from the surface are, therefore, associated with the adhesion of the particles on the solid surface. Consequently, investigation of the adhesion of the dust particles on TiN coated surface is fruitful in terms of maintaining solar energy harvesting device efficiency in harsh environments.

Considerable research studies were carried out to examine surface characteristics of TiN coating in relation to solar energy applications. The optical properties of TiN-based spectrally selective solar absorbers were studied by Gao et al. [7]. They showed that the SS/TiN/Al_2O_3 coating exhibited good thermal stability in a vacuum at 500 °C for 5 h with enhanced absorptance and reduced emittance. The

* Corresponding author at: Department of Mechanical Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia.
E-mail address: bsyilbas@kfupm.edu.sa (B.S. Yilbas).

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characterization and performance evaluation of Ti/AlTiN/AlTiON/AlTiO high temperature spectrally selective coatings for solar thermal power applications was investigated by Barshilia [8]. He demonstrated that the absorber coating displayed improved adhesion, UV stability, corrosion resistance, and thermal stability in air and vacuum with high absorptance and low emittance. A review on physical vapor deposited (PVD) spectrally selective coatings for mid and high temperature solar thermal applications was presented by Selvakumar and Barshilia [9]. They indicated that solar selective coatings based on transition metal nitrides, oxides and oxynitrides hold great potential for high-temperature applications because of their excellent mechanical and optical properties, which were yet to be commercialized. Investigation of optical properties of solar absorber based on cermet of titanium nitride in SiO_2 deposited on lanthanum aluminate was studied by Cao et al. [10]. The findings revealed that the optimized cermet contains TiN with a volume fraction of 60% and 65% demonstrated an absorptance higher than those of ~95% before annealing and ~94% after annealing at 700 °C, which appeared to be useful for especially concentrated solar applications. A refractory selective solar absorber incorporation TiN thin coating was examined by Jiang et al. [11] for the high performance thermochemical steam reforming process. They showed that the selective surface of TiN coating resulted in superior performance for steam reforming and hydrogen production rate at high surface temperatures. A study of porous titanium nitride microspheres in relation to dye-sensitized solar cells was carried out by Wang and Liu [12]. They indicated that the dye-sensitized solar cell with this unique structure resulted in a high conversion efficiency of 6.8%, which was favorably comparable with the cell based on a conventional platinum counter electrode. Solar selective absorbing coatings TiN/TiSiN/SiN prepared on stainless steel substrates were investigated by Feng et al. [13]. They demonstrated that the solar selective absorbing performance of the Cu/TiN/TiSiN/SiN did not show significant changes after they were heat-treated up to 700 °C in vacuum. An optimization study of TiAlN/TiAlON/Si_3N_4 coatings for solar absorber applications was carried out by An et al. [14]. They analyzed the reflectance spectrum of the coatings and indicated that the optimized coating resulted in a solar absorptance and thermal emittance of 94.6% and 5.2% at 400 K, respectively. A new TiN coating combining broadband visible transparency was introduced by Smith et al. [15]. They showed that by depositing thin films resulted in the surface reflection in the near infrared region. This, in turn, made it possible to produce films which transmit daylight neutrally at reasonably high levels, while still maintaining low emittance and solar control in the region of the near infrared radiation. A new structure of durable metallic thin film contacts for solar cells was investigated by Matenoglou et al. [16]. They used stoichiometric titanium nitride (TiN) with a thin non-stoichiometric titanium nitride (TiNx) buffer layer giving the desirable mechanical properties and metallic behavior. They showed that the metallic contacts remained cohered during the scratch test and coating strongly adhered to the substrate surface. Solar selective absorber coatings, consisting in a TiAlNx / TiAlNy tandem absorber with low (metallic-like) and high (semiconductor-like) nitrogen content, and an Al_2O_3 antireflective coating, were studied by Soum-Glaude et al. [17]. They presented the total hemispherical emittance of the coatings in terms of hemispherical directional reflectance spectra measured at different angles and indicated that using the near normal hemispherical emittance could be a good approximation for the estimation of the total hemispherical emittance. Nanostructured thin films for solar selective absorbers and infrared selective emitters were examined by Ollier et al. [18]. They showed that novel pathway for producing low cost nanostructured materials created new opportunities for solar capture in concentrated solar power, solar thermophotovoltaics, solar thermo-electrical generators and for infrared emission control in thermophotovoltaic technologies. Durability of different selective solar absorber coatings in environments with different corrosivity were investigated by Diamantino et al. [19]. They demonstrated that the outdoor exposure testing sites could be used for reliable way to verify the corrosion resistance of new materials and products and the evolution of optical properties degradation of absorber surfaces in the presence of high concentration of contaminants. A degradation study for selective solar absorber surfaces in solar thermal collectors was carried out by Fernandes et al. [20]. The findings revealed that electrochemical impedance spectroscopy (EIS) allowed for the assessment of mechanistic information on the degradation processes, especially if equivalent circuits were used, providing quantitative data that could easily relate to the kinetic parameters of the system.

On the other hand, environmental dust and its effects on surfaces become an interest to maintain the performance of solar energy harvesting systems in harsh environments. Effect of mud drying temperature on surface characteristics of a polycarbonate PV protective cover was studied by Yilbas et al. [21]. They showed that compounds of alkaline (Na, K) and alkaline earth metals (Ca) in dust particles dissolved in condensed water while forming chemically active mud solution, which settled at the interface between mud and polycarbonate surface under the gravitational force. This had a detrimental effect on cleaning of dusted polycarbonate surface because of the mud solution; in which case, upon drying, it increased adhesion between dry mud and surface as well as modified microhardness and surface texture of polycarbonate surface. A study on the wear, optical and electrical characteristics of dry cleaned PV solar panels was carried out by Al-Shehri et al. [22]. They indicated that no permanent or significant negative impact occurred affecting the solar panels performance when the brush-based dry cleaning was introduced removing dust from the panel surfaces. The mechanics of dust removal from rotating disk in relation to self-cleaning applications of PV protective cover were examined by Rifai et al. [23]. The findings revealed that centrifugal force remained higher than the adhesion, friction, drag, lift, and gravitational forces in the region away from the rotational center. The dust particle size and rotational speed significantly influenced the rate of dust removal from the disk surface. The surface characteristics of the laser textured silicon wafer and effect of mud adhesion on hydrophobicity were investigated by Yilbas et al. [24]. They demonstrated that laser textured surface composed of micro/nano poles and fibers, which in turn improved the surface hydrophobicity significantly. In addition, the formation of nitride species contributed to microhardness increase and enhancement of surface hydrophobicity due to their low surface energy. The mud residues did not influence the fracture toughness and microhardness of the laser textured surface; however, they reduced the surface hydrophobicity significantly. Characterization of dust particles collected from PV modules in the area of Dhahran, Kingdom of Saudi Arabia, and its impact on protective transparent covers for photovoltaic applications was studied by Mehmood et al. [25]. They showed that dried mud films required large tangential force removing the dry mud from glass PV cover, which was higher than that of the polycarbonate PV cover. The effect of environmental dust particles on laser gas assisted nitriding and sol–gel coating of alumina surfaces was examined by Yilbas et al. [26]. They demonstrated that the laser treated and sol–gel coated alumina surfaces provided superior surface characteristics in the harsh environments because of weak adhesion between the mud formed from the dust particles and the coating surface. This was associated with the small texture height of the sol–gel coating, which lowered the area of the interfacial contact between the mud and the coated surface, and relatively lower surface energy of the sol–gel coating as compared to that of the laser treated surface. The sol–gel coating did not alter the optical characteristics of the laser treated surface. Laser gas assisted texturing of alumina surfaces and effects of environmental dry mud solution on surface characteristics were studied by Yilbas et al. [27]. The findings revealed that laser texturing resulted in superhydrophobic surface. The mud solution modified the surface texture characteristics of the laser treated workpieces; in which case, surface hydrophobicity reduced significantly. The residual stress was compressive in the surface region of the laser textured workpiece and the mud solution increased