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Spectral selective surfaces for concentrated solar power receivers by laser sintering of tungsten micro and nano particles

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ABSTRACT

Spectral selective surfaces for concentrated solar power receivers have been fabricated by laser sintering of tungsten micro and nano particles on stainless steel substrate under atmospheric pressure. Solar absorptance of ~83% has been experimentally measured for laser sintered tungsten layer and thermal emittance of ~11.6% at 300 K was computed based on the IR reflectance measurement. This high solar absorptance and low thermal emittance was achieved by a one micron thick laser sintered layer having sub-micron surface roughness with random spacing in the range from nanoscale to 5 μm. Laser sintering has not been applied for fabrication of solar receiver coatings and the first experimental demonstration is presented in this paper. Laser sintering under atmospheric pressure is a cost effective method for solar thermal applications.

1. Introduction

Concentrating solar power (CSP) or solar thermal systems is a growing sector as an alternative energy source. Besides consumer applications, solar thermal energy also has tremendous potential for space applications. NASA and other space agencies have researched into utilizing solar thermal energy for rocket propulsion applications due to higher performance than chemical propulsion. CSP is not only limited to conventional rockets, but can also provide propulsion and on-board power for mini and micro satellites in space. For a higher overall conversion efficiency, solar power receivers need to have high photothermal conversion at very high operating temperatures of $>500\ ^\circ$C. In order to achieve high photothermal conversion efficiency, the receiver needs to have high solar absorptance $(\alpha)\geq 95\%$, and low thermal emittance $(\varepsilon)\leq 10\%$ at high operating temperature. For these surfaces to have high α in the solar spectral region, for wavelengths $(\lambda)\leq 2\ \mu$m, and low ε in the infra-red (IR) region, for $\lambda\geq 2\ \mu$m, they need to be spectrally selective.

Currently, commercial spectral selective coatings for receivers show good performance and stability up to 500 °C in vacuum but performance degrades due to oxidation [1]. Current manufacturing techniques with $\alpha>90\%$, and $\varepsilon<10\%$ involve vacuum fabrication techniques making the process expensive.

Materials that have intrinsic optical properties to provide high spectral selectivity, i.e. $\alpha>95\%$ and $\varepsilon<10\%$ at temperatures higher than 500 °C, are not found in nature. Metals like gold, silver, etc. have low thermal emittance but also a very low solar absorptance. Transparent materials like oxides, nitrides, and carbides have extremely low absorptance and very high emittance. There have been previous attempts by researchers to use semiconductors like silicon (Si) and germanium (Ge) as absorber surfaces [2]. Si and Ge have relatively high solar reflectance and thus broadband antireflection coatings need to be used to increase α. However, even with the antireflection coatings, the IR reflectance is low which contributes to high ε. Also, the performance degrades at higher temperatures due to thermal oxidation. Thus a combination of different materials is needed to be used as receiver surfaces for CSP.

Multilayers of dielectric and metal films are stacked to form the absorber surface. These layers achieve spectral selectivity by utilizing partial absorptance in metal films, interference due to multiple layers [3], and IR reflectivity from metals. Several multilayer absorbers using different metals (e.g., Mo, Ag, Cu, and Ni) and dielectric layers (e.g., Al_2O_3, SiO_2, CeO_2, and ZnS) have been investigated for CSP applications [2]. The inter-diffusion between layers at higher operating temperatures causes performance degradation. The manufacturing of these layers requires a vacuum environment and high cost equipment to control the precise thickness of the films which makes it an expensive process.

Ceramic–metal composite (cermet) is a mixture of metallic particles in a dielectric host. Cermet layers deposited onto a

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metallic film have been used for spectral selectivity. The cermet layers act as absorbers in the solar region [2] and the underlying metal layer acts as a reflector for IR to keep the emittance low. Cermet layers serve as a graded index material due to which the reflection of solar spectrum is reduced and the absorptance is increased due to electromagnetic (EM) wave interaction with metal particles and interference phenomenon. The multilayer structure of cermets and metal layer has been fabricated and characterized [4–10] and can achieve relatively high solar absorptance and low thermal emittance. However, performance degrades when these layers are exposed to air due to oxidation at higher temperatures. In addition, like other methods, the manufacturing cost of these cermet layers is extremely high due to the need of vacuum fabrication techniques.

Surface texturing of materials has been applied for solar energy applications [2]. Texturing Si is a good way to significantly increase solar absorptance for solar cell applications. For CSP, cermets and metals have been textured to achieve solar selectivity. Optical trapping of solar light through multiple reflections results in high solar absorptance. Usually, it is easier to achieve high solar absorptance but keeping emittance low is a challenge [11–15]. Also, the performance of textured surfaces drops due to oxidation at high temperatures. There have been some attempts of texturing materials in air environment [16] but have yet to show promising results. There is a large need to overcome the limitations of previous methods and develop highly efficient spectral selective surfaces at relatively lower manufacturing cost that can operate to temperatures above 500 °C.

In this paper, we report a new approach to fabricate spectral selective surfaces using pulsed laser sintering of tungsten metallic micro and nano particles under atmospheric pressure. Laser sintering has been used before for fabrication of coatings using high temperature materials [17,18] but it has not been investigated for fabrication of spectral selective surfaces required in CSP systems.

Controlling the surface roughness of the sintered layer is the key to achieving spectral selectivity. Previously, sub-wavelength periodical tungsten (W) structures have been fabricated by fast atom beam etching to have $\alpha \sim 82\%$ and $\varepsilon \sim 5.6\%$ at 400 K and 15.9% 1200 K [13]. The fabricated sub-micron holes on tungsten can cause standing wave resonances that have been attributed to increase broad wavelength absorptance [13]. However, this required expensive tungsten substrate and complex fabrication process. Sub-wavelength structures on metal surfaces can increase solar absorptance due to surface plasmon absorption [19,20] and also due to the surface behaving like graded index medium thus providing antireflection [13,19]. IR reflectance from sub-wavelength structures on metal surface can be kept very high because the IR wavelengths are much longer than the dimensions of surface roughness and therefore the surface appears smooth and radiates as a flat surface [14]. In this study we show that random sub-wavelength structures can be obtained through laser sintering process at atmospheric pressure, allowing fabrication of low cost high efficiency receivers for solar thermal applications.

2. Experiment

During pulsed laser sintering, a beam is focused onto metallic particles and light gets absorbed thus raising the temperature of the particles. If the temperature is high then the surface of the particles melt and molten particles form necks adjacent to each other forming a continuous layer. For large area sintering, the sample is scanned under the laser beam using a computer controlled X–Y stage. Fig. 1 below shows the laser sintering concept.

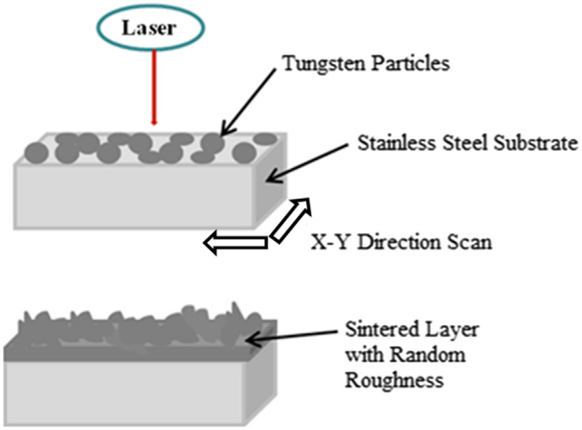

Fig. 1. Laser is scanned across the substrate and it irradiates and melts the metallic particles causing them to bind together to form a sintered layer.

Laser sintering of W micro (1–5 μm) and nano (80–100 nm) particles, supplied by SkySpring Nanomaterials Inc. was carried out on stainless steel (SS) substrate to form a spectral selective layer. Tungsten was chosen as a material of choice because it intrinsically has relatively high absorptance in the solar spectrum and low emittance in the IR. The tungsten powder was put in a beaker containing isopropyl alcohol and the mixture was then ultrasonicated for 5 min. The ultrasonication was done to break the agglomeration of tungsten nanoparticles. A dropper was then used to deposit the solution mixture from the beaker onto a SS substrate and it was kept aside at room temperature for the alcohol to evaporate. After approximately 20 min, the alcohol evaporated leaving only W powder on SS substrate, which we refer to as sample. This sample was then mounted on a computer controlled X–Y stage for laser sintering. A 1064 nm wavelength laser with a repetition rate of 50 kHz and a lens with focal length of 40 mm were used for laser sintering. The laser energy density used for sintering varied from 0.8 to 1.3 J/cm^2. The laser beam was incident on the sample as it was scanned in horizontal and vertical directions resulting in sintered W layer on SS. The scan rate of the X–Y stage was 1 mm/s. After this first laser scan, tungsten powder was again deposited on the sintered region and the same procedures as listed above were followed for the second scan. Laser sintering was carried out under atmospheric pressure. Solar absorptance measurement was done using an integrating sphere, supplied by Labsphere Inc., and laser wavelengths of 532 nm, 633 nm, 1064 nm, and 1550 nm. Reflectance measurements in the IR were done using a continuum IR microscope that was purchased from Thermo Fisher Scientific Inc.. The sample was illuminated by IR wavelengths ranging from 4 to 12 μm and then reflected power was measured to provide a reflectance versus wavelength curve. The IR microscope has the ability to collect reflected light at an angular range of $+/-35^\circ$ from normal to the sample. Emittance was calculated based on experimental reflectance data and blackbody irradiance spectrum at 300 K.

3. Results and discussion

3.1. Morphological study of laser sintered W micro and nano particles

Fig. 2a shows a scanning electron microscope (SEM) image of raw tungsten powder. Most particles are sub-micron (80–200 nm) in size but some of them are in the rage of 1–5 μm. After laser sintering, a sintered layer of W is formed as shown in Fig. 2b. The layer is continuous without any cracks or discontinuity. Fig. 2c