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ScienceDirect

Solar Energy 96 (2013) 113–118

SOLAR ENERGY

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Spectral properties and thermal stability of solar selective absorbing AlNi–Al_2O_3 cermet coating

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Received 24 April 2013; received in revised form 2 July 2013; accepted 16 July 2013
Available online 9 August 2013

Communicated by: Associate Editor Yanjun Dai

Abstract

A new solar selective absorbing coating of AlNi–Al_2O_3 cermet multilayer is designed and prepared on Cu or stainless steel (SS) substrate by magnetron sputtering. The coating consists of an IR-reflective metallic layer, an absorption bilayer and an anti-reflection layer from substrate to top. The IR-reflective metallic layer is Cu or Mo. The absorption bilayer consists of a high metal volume fraction (HMVF) AlNi–Al_2O_3 cermet sublayer and a low metal volume fraction (LMVF) AlNi–Al_2O_3 cermet sublayer. The anti-reflection layer is Al_2O_3. The optical performance (α/ε) of the coating is 0.94/0.07 on Cu substrate and 0.95/0.078 on SS substrate by optimizing the metal volume fraction and thickness of each layer. The samples deposited on SS substrate were heated at 500 °C for 138 h and 284 h in vacuum to evaluate the optical stability. Experimental results showed that the high temperature stable AlNi intermetallic compound, instead of Mo in the traditional Mo–Al_2O_3 coatings, displayed a good thermal stability at 500 °C. There is no significant change appearing in the optical properties of the coating after the heat treatment. It means that the new coating is a good potential candidate as a high temperature solar selective absorbing coating for parabolic trough concentrated solar power (CSP).

Keywords: AlNi–Al_2O_3 cermet coating; Spectral selectivity; Thermal stability; Magnetron sputtering

1. Introduction

Solar spectral selective absorbing coating is a critical component of a solar photo-thermal conversion absorber, which requires a high absorptance in the wavelength 300–2500 nm and a low thermal emissivity at the operating temperature. This is realized by low reflectance (near zero) of an absorber surface in the main solar radiation spectrum and high reflectance (close to one) in the IR region (>2500 nm) (Zhang et al., 1996).

In the last several decades, magnetron sputtering technology has been developed to deposit solar selective coatings for high temperature usage, such as Pt–Al_2O_3 (Nuru et al., 2012) and Cr–Al_2O_3 (Yin et al., 2009) cermet coatings. By computer modeling calculations, Zhang and Mills (1992) predicted a double cermet layer structure. The typical coating structure from surface to substrate consists of an anti-reflection layer composed of a transparent ceramic material that enhances solar transmission, a low metal volume fraction (LMVF) cermet solar absorption layer, a high metal volume fraction (HMVF) cermet solar absorption layer, which forms interference absorption bilayer, and an IR-reflective metallic layer that decreases the IR emission. Many experiments have proved that the coating structure has better solar spectral selective performance. Based on above coating structure, a large number of solar selective coating series, such as Mo–SiO_2 (Wang et al., 2011), M–AlN (Zhang, 1998), Ni–NiO (Adsten et al., 2000), W–Al_20_3 (Antonaia et al., 2010), Ag–Al_2O_3 (Barshilia et al., 2011), Mo–Al_2O_3 (Lanxner and Elgat, 1990; Xinkang et al., 2008) HfMoN/HfON/Al_2O_3 (Selvakumar et al.,

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http://dx.doi.org/10.1016/j.solener.2013.07.012

2012) and TiAlN/TiAlON/Si_3N_4 (Biswas et al., 2008; Barshilia et al., 2008; Godinho et al., 2010) have been studied as an absorber surface.

However, parabolic trough concentrated solar power (CSP) requires such kinds of solar selective absorbing coatings working at high temperature (>400 °C). Hence, thermal stability of a coating is becoming a critical problem, which determines the working lifetime of a solar absorber. In the cermet layer of a solar selective coating, single metal particles are usually dispersed in the ceramic matrix layer. However, single metal particles are easy to diffuse, congregate or to be oxidized. This causes deterioration in optical properties of the coating at high temperature. For example, Mo is easy to diffuse in Al_2O_3 ceramic matrix and interfacial boundary at high temperature above 500 °C (Xinkang et al., 2008). If we choose the high temperature stable binary alloy, such as AlNi to disperse in the Al_2O_3 matrix, instead of Mo in Mo–Al_2O_3 coating, maybe it could restrain the diffusion and oxidation, and improve the thermal stability of the absorbing coating at high temperature. We know that the AlNi alloy owns good thermal stability and better anti-diffusion and anti-oxidant effects than single Mo or Ni metal particles (Mahesh et al., 2009). In this paper, we choose AlNi binary alloy to substitute Mo single metal to prepare a new high temperature stabilized AlNi–Al_2O_3 cermet selective absorbing coating. To our knowledge, NiAl–Al_2O_3 solar selective absorbing coating has never been mentioned for parabolic trough CSP applications up to now.

Based on the double cermet layer structure, we prepared high metal volume fraction AlNi–Al_2O_3 layer (HMVF), low metal volume fraction AlNi–Al_2O_3 layer (LMVF) and Al_2O_3 anti-reflection layer from bottom to top on Cu substrate as solar absorbing coating by DC and RF magnetron sputtering. Here Cu works as an IR-reflective metallic layer which owns good infrared reflectance. We also deposited the coating on SS substrate and a Mo layer was deposited between SS and HMVF as IR-reflective metallic layer. The optical properties and thermal stability of the coating were investigated.

2. Experimental

Metallic Mo, alloy AlNi and ceramic Al_2O_3 in the coating were deposited using DC and RF magnetron sputtering, respectively. Mo (99.99% purity) metallic target, Al_2O_3 (99.99% purity) ceramic target and AlNi (99.99% purity) alloy target are mechanically clamped to three planar sputter sources which are mounted horizontally on the base of the vacuum chamber. All of the Mo, Al_2O_3 and AlNi targets have a diameter of 60 mm and thickness of 4 mm. The vacuum chamber was pumped to a base pressure of 4×10^{-3} Pa, and then putting Ar gas into the chamber, the sputtering pressure was changed by adjusting the valve of the molecular pump. The parameters for the deposition of Mo, AlNi and Al_2O_3 are listed in Table 1. Prior to the deposition of the multilayer films, Cu or SS substrate (25 mm × 25 mm × 1 mm) was rinsed in acetone and ethanol baths for 15 min. For the layers of HMVF and LMVF, the expected change of the metal volume fraction is adjusted by the sputtering time of AlNi and Al_2O_3 when the substrate rotates facing the two targets alternately. There are many AlNi minilayers (2–6 nm) and Al_2O_3 minilayers (3–8 nm) alternately deposited, forming the AlNi–Al_2O_3 absorption layer, i.e. HMVF or LMHF sublayer. For example, when we deposit AlNi minilayer with the thickness of 6 nm and Al_2O_3 minilayer with 4 nm for six times alternately, then the metal volume fraction and thickness of the absorption layer are 60% and 60 nm, respectively.

The deposition rates of the Mo, AlNi alloy and ceramic Al_2O_3 were derived by measuring the thickness of the films using a Tencer P-10 α-step surface profiler. The optical reflectance was measured by UVPC3100 spectrophotometer in the wavelength range of 0.2–2.6 μm and Shimadzu IR-470 Infrared Spectrophotometer in the range of 2.6–25 μm. The nearly normal emissivity was measured by NEM-80 normal emissivity tester at 80 °C. The structure of the films was investigated by X-ray diffraction (XRD) on a Dmax diffractometer with Cu Kα (40 kV, 20 mA, $\lambda = 0.15406$ nm) radiation with the 2θ angles in the range 20–90° in the scanning step of 0.02°. Surface morphology was observed by a JEM-100CX scanning electron microscopy (SEM). The evaluation of thermal stability was carried out by putting the coating sample at 500 °C for 12 h, 138 h and 284 h, respectively, in a vacuum quartz tube with a pressure of 5×10^{-2} Pa.

3. Results and discussion

3.1. Optimization and characterization of AlNi single layer

Figs. 1 and 2 show XRD patterns of the single AlNi layer prepared under different sputtering powers on Cu and SS substrates, respectively. When the target power density was below 2.93 W/cm^2, only the diffraction peaks from Cu or SS substrate were observed. It is only when the target power density was increased above 2.93

Table 1
The parameters for the deposition of Mo, AlNi and Al_2O_3 layers.

Phase	Sputtering method	Ar gas (sccm)	Total pressure (Pa)	Sputtering distance (mm)	Voltage (V)	Current (A)	Power density (W/cm^2)
Mo	DC	50	0.75	60	240	0.7	5.94
AlNi	DC	50	1.0	60	460	0.18	2.93
Al_2O_3	RF	50	1.0	60	1100	0.3	5.66