

High temperature spectral selective TiC-Ni/Mo cermet-based coatings for solar thermal systems by laser cladding

Qian Wei, Xu-Ming Pang*, Jian-Xin Zhou, Cheng Chen

School of Mechanical and Power Engineering, Nanjing Tech University, Nanjing 211816, China

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ABSTRACT

Thermal instability and quite high infrared emissivity at high temperature is one of the great challenges in the development of concentration solar power (CSP). Herein, a new single layer multi-scaled nanostructured TiC-Ni/Mo cermet-based spectral selective coating fabricated by the laser cladding method on stainless steel at atmospheric pressure are explored in this study. This method helps to attain the desired coating roughness which the solar absorptance of $\sim 86.2\%$ has been experimentally measured and thermal emissivity of $\sim 4.2\%$ at 300 K was calculated. After anneal at 600 °C for 200 h in air, the coating still showed a low thermal emissivity of $\sim 4.7\%$ and a high absorptance of $\sim 84.7\%$. A high selective receiver efficiency of $\sim 82.0\%$ has been achieved for laser cladding coatings. This low thermal emissivity and high solar absorptance was got by a single laser cladding layer having sub-micron surface roughness using fractal nanostructure with characteristic metal particle sizes in the range from nanoscale to microscale. These results show that the laser cladding TiC-Ni/Mo cermet-based absorbing coating would be suitable for high temperature application because it can satisfy the operating temperature of ≥ 600 °C in air.

1. Introduction

Solar energy is the most environment-friendly renewable energy resource available. Currently, thermal conversion has been commercially carried out in concentrating solar power (CSP) systems, in which the solar receivers are one of the key parts to dominate the entire performance of CSP. In order to increase the efficiency of the power generation system, it requires the heat transfer fluid (HTF) with materials of high photo-thermal conversion at high temperatures of ≥ 600 °C. In addition, receivers needs to be coated with spectral selective coatings that have high solar absorptance(α) for wavelength (λ) < 2.5 μm and low thermal emittance (ϵ) in the infrared region (IR) at $\lambda > 2.5$ μm (Toor et al., 2016). Accordingly, novel spectral selective surfaces which have better optical properties and excellent thermal tolerance are desired for solar thermal power generation.

In recent years, various novel methods have been used to prepare spectrally selective solar absorber with various structures such as electrochemical plating, plasma spraying, hydrothermal method and magnetron sputtering, etc. Compared to these methods, laser cladding and laser sintering have been widely used to fabricate hard, high thermal stable and wear resistance coatings (Riquelme et al., 2017; Sahoo and Masanta, 2017; Wang et al., 2017). The laser sintering method has been used previously for fabrication of a single layer

spectral selectivity coating but it was not investigated for thermal stability (Shah and Gupta, 2013). Laser cladding can appear in form of solid-state cladding or liquid-phase cladding. During solid state cladding, the melting point and the binding takes place at temperature much higher than the consolidation of powder occurs because of diffusion of atoms among adjacent particles. Not only partial melting, but also full melting of the particles can occur during liquid phase cladding and dense coatings can be formed because of this mechanism as well (Pang, 2017). Our previous studies indicated that the laser cladding is one of the good candidates used in the realm of the spectral selective absorbing coatings. Besides, multi-layers of dielectric and metal films are stacked to form the absorbing surfaces, which have been studied for CSP applications. Several multi-layer absorbers use different metals (e.g. Mo, Ni and Ag) and dielectric layers (e.g. Al_2O_3 , SiO_2) (Conibeer et al., 2006; Lu et al., 2011; Zhan et al., 2012). But, the fabrication of these layers needs a vacuum environment and high cost equipment to control the precise thickness of the films which makes it an expensive process. The inter-diffusion between layers at higher operating temperatures leads to properties degradation (Ambrosini et al., 2011).

However, materials that have intrinsic optical performances and excellent stability at high temperature are not found in nature. A single layer spectral selective coating of single-phase tungsten nano and micro particles for solar thermal receivers by laser sintering have been

* Corresponding author.

E-mail address: pxmkf@njtech.edu.cn (X.-M. Pang).

Table 1
Chemical composition of AISI 316 substrate.

Elements	C	Si	Mn	P	S	Ni	Cr	Mo	Fe
Wt%	≤0.08	≤1.0	≤2.0	≤0.045	≤0.03	10–14	16–18	2.0–3.0	Bal.

Table 2
The nomenclature for the composite coatings and their composition (M represents Micro-size particles, N represents Nano-size particles).

Sample no.	TiC (M)		Ni(M)		Mo(M)		Ni(N)		Mo(N)	
	wt%	mol%	wt%	mol%	wt%	mol%	wt%	mol%	wt%	mol%
1-A	60	64.59	20	21.97	20	13.44	0	0	0	0
2-B	60	62.73	27	28.79	13	8.48	0	0	0	0
3-C	60	61.96	30	31.60	10	6.44	0	0	0	0
4-D	60	61.45	32	33.43	8	5.12	0	0	0	0
5-E	60	60.96	34	35.24	6	3.80	0	0	0	0
6-F	60	61.96	15	15.80	5	3.22	15	15.80	5	3.22

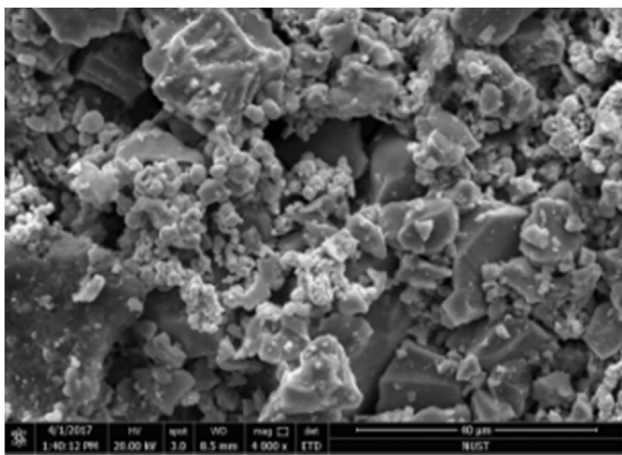


Fig. 1. SEM image of depositing TiC-Ni/Mo coating.

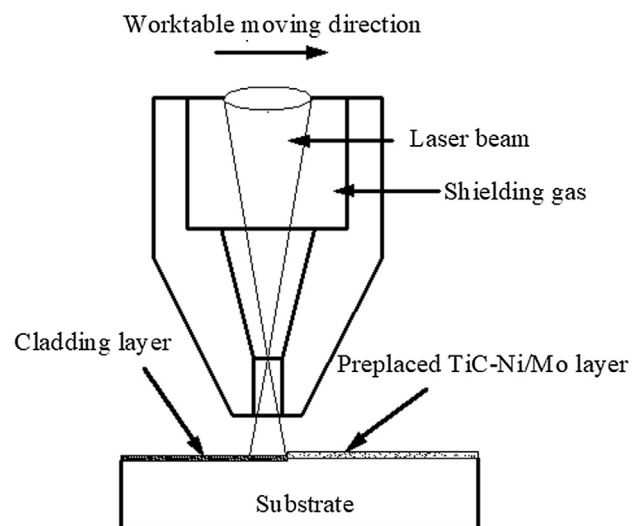


Fig. 2. Schematic diagram of laser cladding coating process.

fabricated on stainless steel (SS) substrate at atmospheric pressure that has solar absorptance of $\sim 83\%$ and thermal emittance of $\sim 11.6\%$ at 300 K (Shah and Gupta, 2013). The nickle-pigmented aluminium oxide selective absorber coating showed a higher solar absorptance of $\sim 90\%$, but the unstable microstructure of the coating is the major problem for the selective coatings of high temperature application at high temperature (Wazwaz et al., 2002). Thus a combination of different materials is required to be used as absorber surfaces for CSP.

Particularly, enormous efforts have been made to develop high temperature solar selective absorber coatings. Ceramic like titanium carbide (TiC), aluminium oxide (Al_2O_3) and silicon dioxide (SiO_2), silicon carbide (SiC), etc. have many unusual features including high hardness, good stability at high temperature and high thermal conductivity (Viswanathan et al., 2013; Riquelme et al., 2017; Sahoo et al., 2015; Bichotte et al., 2017). Among ceramic particles used as reinforcement, TiC is one of the prominent choices due to its good hardness, high melting temperature, excellent thermal conductivity, durability at high temperature and low coefficient of friction against metallic counterpart (Di et al., 2011). It is revealed that a layer of ceramic particle can reinforce metal matrix composite (MMCs) on the surface of base materials fabricated by high energy density deposition methods like laser cladding, cladding melting can enhance the surface properties without affecting bulk characteristics (Berger, 2015). Interfacial materials like Ni and Co, those are preserving high wetting

property with both TiC particles and stainless steel (SS) require to provide to acquire a suitable bond between the substrate and reinforced ceramic particles (Nowotny et al., 2014).

Besides the thermal stability, low thermal emissivity is another evaluation standard for high temperature solar selective absorber coatings. According to the formula provided in (Cindrella, 2007), the emissivity is proportional to T^{-4} (T is the work temperature). Therefore, the issue of thermal emissivity should be place a higher priority than the absorptivity to be paid attention for high temperature absorbing coatings.

In this paper, based on the investigation of a single-phase tungsten coating prepared by laser sintering method, with an objective to boost the thermal tolerance of coatings, TiC-Ni/Mo cermet-based absorber coatings have been prepared with 5 different contents of Ni and Mo by laser cladding. In order to further improve the solar absorptance and strength thermal stability of TiC-Ni/Mo cermet-based absorber coatings, we introduced nano particles to fabricate multi-scaled nanostructured TiC-Ni/Mo cermet-based absorber coatings, laser cladding of Nickel (Ni) and Molybdenum (Mo) metallic micro and nano particles and Titanium carbide (TiC) ceramic micro particles on stainless steel substrate were fabricated to form spectral selective coatings under

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