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Evolution of structure and infrared radiation properties for ferrite-based amorphous coating

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ABSTRACT

The ferrite-based amorphous coatings with high infrared radiation properties have been successfully prepared on the surface of carbon steel substrate by plasma spraying process. The phase, morphology, microstructure, thermal behavior and infrared emissivity were determined by X-ray diffraction, scanning electron microscopy, differential scanning calorimetry and infrared spectroscopy. The prepared coating could keep amorphous structure when the ambient temperature was below 700 °C and it would crystallize gradually with further increasing the temperature. The amorphous structure is confirmed to be constructive for improving the emissivity of ferrite-based coatings, especially in the 3–8 μm band. The emissivity of the amorphous coating obtained by plasma spraying was over 0.8 in 3–8 μm band at 800 °C, which was higher than that of the coating with same composition prepared by conventional brushing method. The excellent thermal shock resistance of the coatings makes them to be good candidates for sensible energy-saving materials, which could work for long term at 1000 °C.

1. Introduction

As fossil fuels shortage and environmental pollution become increasingly serious crisis, considerable attention has been paid to advanced energy-saving materials. Infrared radiation materials with high emissivity, which can effectively improve thermal radiation efficiency of infrared heaters [1,2] and enhance radiation heat transfer [3,4], play a positive impact in energy-saving areas and have been widely used in high energy consumption industries [5–8].

According to the Wien's displacement law and Planck's radiation law [9], the wavelength of infrared radiation peaks value will move toward short wave band as the temperature increased, and the radiant energy in 1–5 μm accounts for 76–86% of the whole infrared radiation energy at high temperature. In the past few decades, great advances have been achieved that the infrared emissivity in 8–20 μm band for the infrared radiation materials has been over 0.9. However, it should be noted that the emissivity in 1–8 μm band at high temperature was still less than 0.6. So, the applications of infrared radiation materials were restricted in high energy consumption industries because of the poor infrared radiation performance in short wave band at high temperature.

Generally, the emissivity in the band of 2.5–25 μm wavelength is significantly associated with the transition of molecular rotational level and the lattice vibration level [10], which are both largely determined by the chemical composition and crystal structure of infrared radiation materials. The ferrites with spinel structure are good choices for infrared radiation materials because of their high infrared radiation performance in whole infrared band and excellent thermal stability at high temperature [11–13]. To improve the infrared radiation properties, enhancing the structure distortion coefficient [14–16] of ferrites was considered to play an important role on improving the infrared emissivity. Consequently, doping impurities or rapid cooling is commonly used to destroy lattice periodicity and preserve the maximum lattice defects during preparing ferrite-based infrared radiation materials [17–19], which can enhance the inharmonic lattice vibration. Unfortunately, it presents slow progress in 3–5 μm band although extensive efforts have been done for years.

It is well known that the amorphous structure presents a long-range disorder and higher disorder distortion coefficient, which can enhance the active anharmonic vibration and improve the

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Table 1
Process parameters of plasma spray.

Parameters	Bond coating	Infrared radiation coating
Current (A)	450	500
Voltage (V)	70	80
Ar (m^3/h)	25	25
N_2 (m^3/h)	10–12	10–12
H_2 (m^3/h)	-	1–5
Powder feed rate (g/min)	20–25	13–15
Spraying distance (mm)	120	80

infrared radiation performance. Nevertheless, the study of amorphous infrared radiation coating for saving energy is rarely reported in literatures. In this work, the ferrite-based amorphous infrared radiation coating was successfully prepared on the surface of carbon steel substrate by plasma spraying technology. The evolution of microstructure and infrared radiation properties of the ferrite-based coating with ambient temperature were investigated in detail.

2. Experimental

All chemicals used in this work were of analytical grade and were used as received without further purification. Firstly, the ferrites with mixed spinel structure were synthesized by solid phase reaction at 1150 °C for 2 h using Fe_2O_3 (51.20 wt.%), CuO (32.42 wt.%), and MnO_2 (16.38 wt.%) as raw materials. Subsequently, the obtained ferrites were crushed, ball milled, and collected by sieving with a screen having grid size of 38 μm. Then the ferrites and SiC powders were mixed uniformly by planet ball mill. Lastly, the agglomerated quasi-spherical infrared radiation composite powders were prepared by spray drying process from the mixtures of the obtained ferrites and SiC powders. In order to enhance the bonding strength between substrate and coating, the surface of carbon steel substrate was pretreated by cleaning, sand blasting, and preheating. A rough and dark infrared radiation coating was prepared by ASP-3000F plasma spraying equipment after the deposition of Ni/Cr/Al/Co bond coating on the surface of pretreated carbon steel substrate. The process parameters of plasma spraying were listed in Table 1.

The phase structures of the obtained ferrites and coatings were investigated by X-ray diffraction (XRD, PHILIPS XPERT PRO, Cu Kα radiation (λ = 1.5418 Å)). The microstructure of infrared radiation powders and coating were characterized by field emission scanning electron microscopy (FESEM, Nova 400 NanoSEM). The thermal properties of the infrared radiation coating were determined by thermal gravimetric analysis and differential scanning calorimetry (TG–DSC, STA449 C, NETZSCH), which was performed at a heating rate of 5 °C/min up to 1000 °C in argon atmosphere. The thermal shock resistance of the coatings was tested by thermal cycle with water cooling. The coatings were visually observed after each thermal shock. The spectral emissivity of the coating samples at 800 °C was determined in the wavelength of 3–20 μm by comparing the radiation of coating sample with a blackbody under the same condition (FT-IR, Jasco-6100). The spectral emissivity value ε was defined using the following formula: $\varepsilon(\lambda) = L(\lambda)/L_b(\lambda)$, where $L(\lambda)$ was radiance of coating sample, $L_b(\lambda)$ was radiance of blackbody.

3. Results and discussion

3.1. Structure analysis of infrared radiation powders

Fig. 1 shows the SEM of infrared radiation powders prepared by spray drying process. The obtained powders are mainly quasi-spherical and only a small amount of particles are irregular (Fig. 1a). The agglomerated particles are composed of a large amount of small irregular tiny particles (Fig. 1b), and the particle size of the quasi-spherical powders was about 20–100 μm. The agglomerated quasi-spherical particles can enhance the flow ability of the infrared radiation powders [20] so that they can be continuously injected into the plasma jet, which is beneficial to high deposition efficiency and more uniform microstructure for the coating.

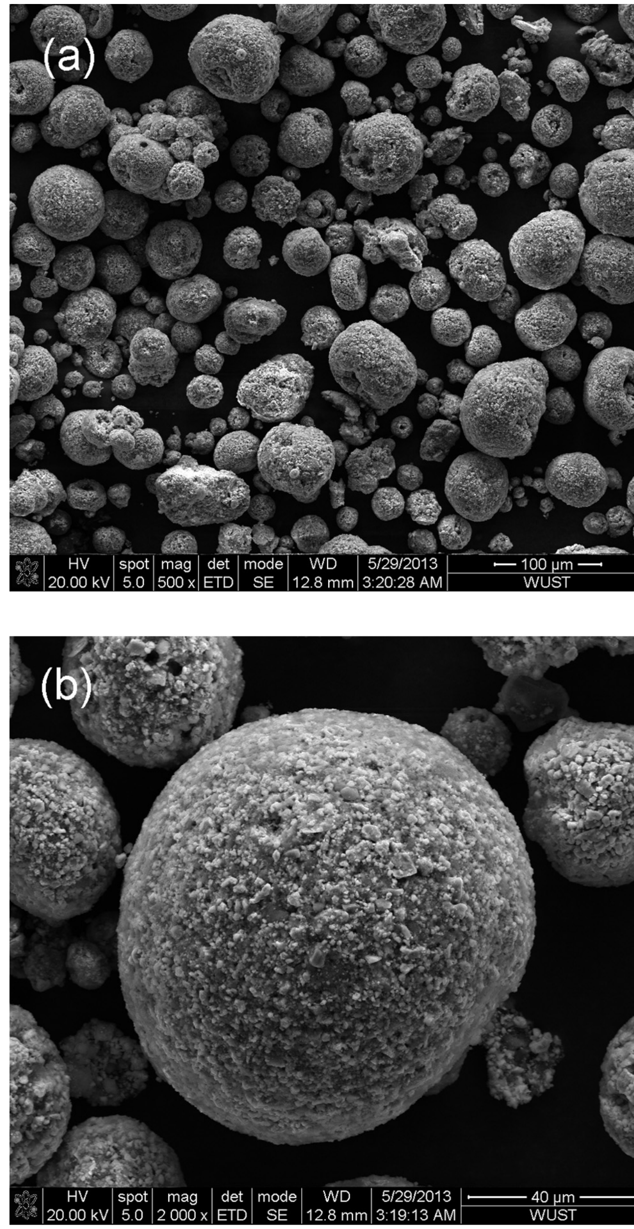

Fig. 1. SEM of the infrared radiation composite powders.

3.2. Structures of infrared radiation coatings

Fig. 2 presents the surface morphology and cross-section microstructure of infrared radiation coating. As shown in Fig. 2a, the coating has a typical laminated structure, and the rough surface increases the coating surface area, which can increase the infrared radiation absorption of the coating [20]. As shown in Fig. 2b, the laminated structure displays high internal density, which means that the coating has high cohesive strength. The coating thickness is in the range of 80–100 μm. Some tiny holes are uniformly distributed in the coating due to the cooling shrinkage of the molten materials, which can reduce the thermal stress and improve the