Surface & Coatings Technology xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Suppression effect of decarburization by dry-ice blasting on plasma-sprayed steel coatings: Structure, wear performance and magnetic properties

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ARTICLE INFO

Article history:
Received 20 December 2013
Accepted in revised form 10 May 2014
Available online xxxx

Keywords:
Steel coating
Atmospheric thermal spraying (APS)
Dry-ice blasting
Decarburization
Magnetic behavior
Wear resistance

ABSTRACT

Steel coatings prepared by atmospheric thermal spraying with dry-ice blasting were studied in terms of phase structure, magnetic and wear behaviors. It was found that dry-ice blasting could suppress the volatilization of carbon during spraying process due to the exclusion effect of carbon dioxide gas sublimated from dry-ice pellets on the oxygen. Moreover, the fractographic observation of the deposited coatings proved the removal effect of dry-ice blasting on the splashing particulates which were distributed with poor bonding strength between the splat layers. In addition, it has been found that the magnetic properties are sensitive to the direction in the coating, although steel coating presents a ferromagnetic character in the parallel and vertical directions. Steel coating deposited with dry-ice blasting possesses a relatively lower saturation magnetization but has a superior wear resistance because of the suppression of decarburization during the spraying process.

1. Introduction

Tool steels containing high chromium and high carbon are commonly subjected to extremely high load due to their high hardness and high wear resistance [1–3]. Atmospheric thermal spraying (APS) has been proved to be a suitable processing method to produce tool steels as an overlay coating if the intended technological applications are pertaining to the surface engineering problems [4,5]. Especially it can be applied to deposit amorphous or nanocrystalline Fe-based magnetic coatings [6,7], owing to its high cooling rate (10^7–10^8 K/s [8]) and low operation cost.

However, plasma-sprayed coatings usually contain oxide layers, inclusions and different pores between the splats. The oxide layers between the splats are probably the result of both surface oxidation of the molten metal droplets in-flight and continued oxidation of the splats on the sample surface as they solidify [9]. The existence of both oxides and interconnected pores in APS coatings usually restricts the realization of perfect properties, such as sliding wear. It has been reported that the sliding wear of thermal sprayed steel coatings could be attributed to splat delamination [10] due to the 'weak links' caused by the oxide veins [11].

In addition, the decarburization of original carbonaceous feedstock during the plasma spraying process is another problem. During the APS process, the melted steel particles are exposed to high temperature and atmospheric environment, the C element in steel can easily react with oxygen. The inherent defects in the preparation of steel coating by APS result in the decrease of hardness and wear resistance.

Dry-ice blasting as a pre-/post-treatment cryogenic method during plasma spraying process was employed in this study to provide an alternative way for suppressing those problems encountered in the deposited steel coatings. The aim of this work is to investigate the effect of dry-ice blasting on the plasma-sprayed coatings and quantify the relationships between the structure, wear resistance and magnetic properties.

2. Materials and experimental procedure

2.1. Materials

A commercially available steel powder ($Fe_{1.4}Cr_{1.4}Mn_{1.2}C$, Sulzer Metco 4052) was used as feedstock material. Fig. 1a illustrates the morphology of the $Fe_{1.4}Cr_{1.4}Mn_{1.2}C$ powder. It displays a spheroidal morphology, which is a general feature of gas atomized powder. Powder size distribution was measured with a laser particle size analyzer (Mastersizer 2000, Malvern Instruments, UK). It exhibits a distribution with D0.1 of 13.98 μm, D0.5 of 25.60 μm and D0.9 of 43.15 μm, as shown in Fig. 1b.

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http://dx.doi.org/10.1016/j.surfcoat.2014.05.012
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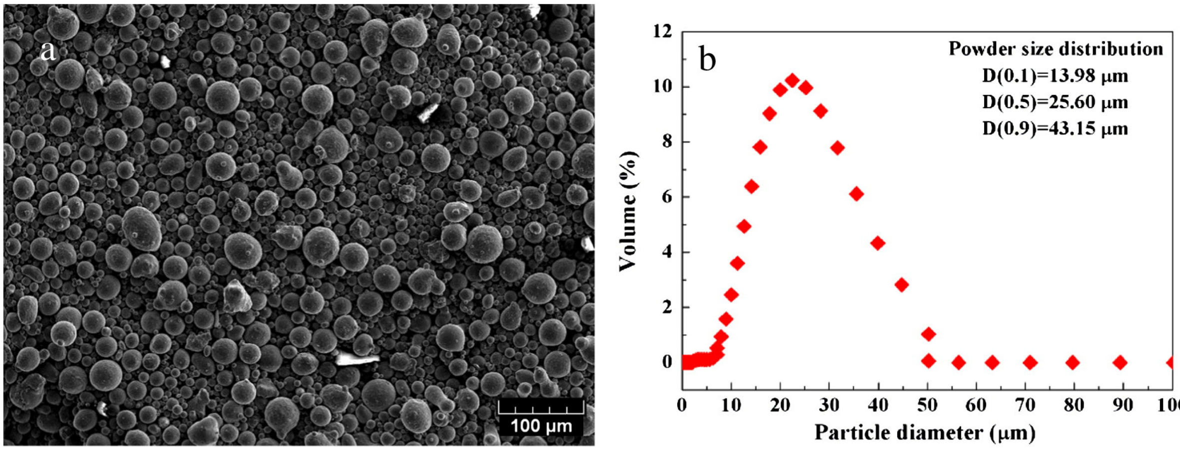

Fig. 1. (a) SEM observation of steel ($Fe_{1.4}Cr_{1.4}Mn_{1.2}C$) powders and (b) size distribution.

2.2. Coating preparation

All specimens were produced by atmospheric plasma spraying using a Sulzer-Metco F4 plasma gun. Argon was used as both plasma-operating and powder carrier gas. Spraying parameters for this material were set up as follows: arc current (600 A), arc voltage (67 V), primary plasma gas (Ar, 60 SLPM), secondary plasma gas (H_2, 9 SLPM), powder carrier gas (Ar, 2.0 SLPM). All the substrates which were fixed in a cylindrical holder (diameter of 160 mm) were sandblasted prior to spraying. Sand-blasting was undertaken using pressure and suction operated machines with alumina grit. The grit particles were angular with a mean size of 500 μm which are supplied by Ampere Alloy Enterprise. The used stainless steel substrate exhibits an average surface roughness Ra of 4.3 μm after the sandblasting. The spraying torch was mounted on the flange of a robot (ABB, Sweden) and moved in front of a cylindrical holder which rotated with a speed of 150 rev/min. The plasma spray distance was fixed at 115 mm.

Dry-ice blasting (Fig. 2) was carried out using a mobile blasting device (ic4000 system, HMRexpert, France), which comprises a similar-Laval nozzle with a rectangular outlet dimension of 9 × 40 mm, a mass flow controller with a pneumatic motor, a storage tank, and a compressed air supplier. For the present work, mass flow rate of dry-ice pellets was 42 $kg \cdot h^{-1}$ under a gas pressure of 0.6–0.8 MPa. The distance between the axis–exit of the dry-ice blasting nozzle and substrates was about 25 mm. The robot was employed to vertically move the spray torch and the dry-ice blasting nozzle with a line speed of 15 mm/s for a uniform and reproducible deposition of coatings. All the sand-blasted substrates were pre-treated for 4 double-passes up- and downwards by dry-ice blasting and the average roughness Ra changes into about 4.1 μm; meanwhile plasma flame was turned on but not providing the powder, which aims at avoiding the condensation arising from the treatment of dry-ice blasting with a long duration. Afterwards, the sending powder system was turned on to deposit coatings. In other words, dry-ice blasting was conducted throughout the deposition process. Considering the distance between the two torches was about 20 mm, the calculated time gap from the dry-ice blasting to the particle deposition was about 0.016 s. The coatings were deposited for 20 double-passes up- and downwards. The temperatures of samples were measured using an infrared pyrometer measurement system.

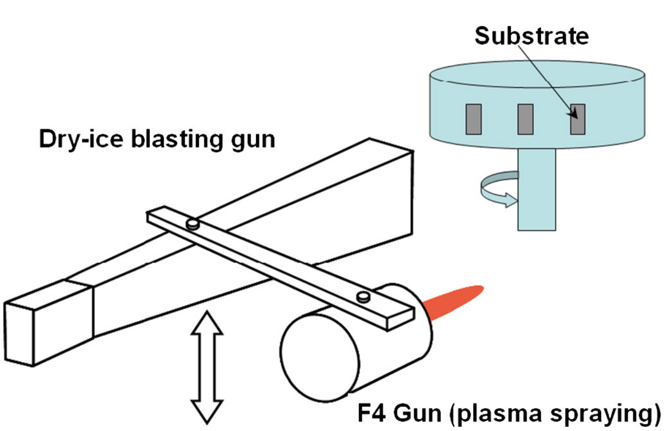

Fig. 2. Schematic diagram of the deposition process by plasma spraying and dry-ice blasting.

2.3. Coating characterization

The as-sprayed coatings were examined by scanning electron microscopy (SEM, JSW-5800LV and 7800F, JEOL). The oxide content and porosity of the as-sprayed coatings were estimated using image analysis. More than 5 photos randomly observed in the polished cross-section were averaged to evaluate them. After the coating preparation, all the samples were analyzed by X-ray diffraction (XRD), which were conducted on a Siemens diffractometer, operating with a cobalt anticathode ($\lambda = 1.78897$ Å) at 35 kV and 40 mA and a scanning rate of $10°min^{-1}$ in a scattering angular range (2θ) of 20–80°.

In addition, free standing coatings were obtained to analyze the oxygen and carbon contents by N, O, H Analyzer and CS-800 Analyzer (ELTRA HRT GmbH Germany) and measure the coating density using Archimedes method by density measuring instrument (AB204, Mettler Toledo, France).

The coating density (g/cm^3) was determined according to Archimedes law from the weight of the sample measured in water and in air using:

$$\rho = \frac{m_a}{m_a - m_w} \times \rho_w \quad (1)$$

where m_a is the coating weight in air (g), m_w is the coating weight in water (g), and ρ_w is the density of water (1.0 g/cm^3).

Magnetic properties, such as saturation magnetization (Ms), were determined from M-H loops measured using a PPMS-9 model vibrating sample magnetometer (Quantum Design, USA) at room temperature. The measurements were realized with a magnetic field applied in the parallel and vertical directions. The maximum magnetic field was fixed at 10^4 Oe.

Please cite this article as: B. Song, et al., Surf. Coat. Technol. (2014), http://dx.doi.org/10.1016/j.surfcoat.2014.05.012