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Influence of microstructure on the optical property of plasma-sprayed Al, Cu, and Ag coatings

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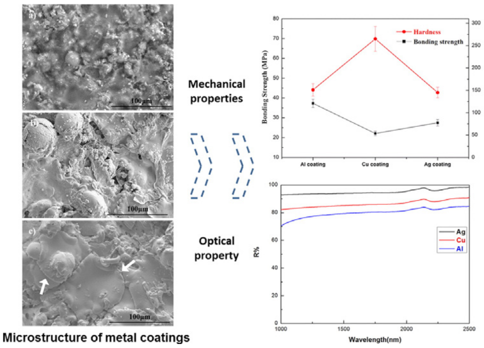
HIGHLIGHTS

- The metallic coatings have no oxidation or over-melting phenomenon deposited by optimal plasma-sprayed parameters.
- The Ag coating can obtain a high reflectivity (98.6%) due to low surface roughness and dense microstructure.
- The splats with disk-shaped morphology in metallic coating contribute to improve the mechanical and optical properties.

GRAPHICAL ABSTRACT



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ABSTRACT

Metal materials have been used as thin films in many optical applications because of its excellent high reflectivity in the near-infrared range. However, studies on thick metal coatings deposited by plasma spraying have rarely been conducted. The current study investigates the relationship between optical property and microstructure for different metal plasma-sprayed coatings (Al, Cu, and Ag) and discusses the corresponding mechanical properties. The phase structure and surface morphology of as-sprayed powders and corresponding coatings were examined by X-ray diffraction and scanning electron microscopy, respectively. The optical and mechanical properties were characterized by UV–visible-near infrared spectroscopy, Multi-Specimen machine testing and Vickers microhardness testing. Results indicate that the optical behavior of metal plasma-sprayed coatings is related to their phase structure, splat microstructure, and surface roughness. Optimization of powders in molten state and the surface microstructure is proposed as an effective method to improve the optical property of these coatings. The molten state and low porosity also help to improve the mechanical properties of the coating materials.

1. Introduction

Atmospheric plasma spraying is a technique wherein particles are heated in the plasma jet at a very high temperature and propelled at high velocity to impact the substrate. The as-sprayed powders are then flattened and solidified in a molten or semi-molten state to form a coating [1–3]. The advantage of this technique is its good ability to spray a wide range of materials from metals to ceramics on substrates of largely varying geometric shapes and sizes. In addition, this technique entails low costs, thus allowing the cheap production of coatings with thicknesses ranging from microns to millimeters at the industrial

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scale. Plasma-sprayed ceramic coatings are often used to improve the heat and oxidation protection, wear, and erosion resistance capabilities of functional pieces [4–8]. Some cermet composite coatings that are deposited by plasma spraying are also widely applied in some industrial fields. Cermet coatings with metal materials as a solid lubricant phase exhibit excellent self-lubricating performance during thermal cycling [9,10].

However, studies focusing on the plasma-sprayed metal coatings, particularly their optical property, are rarely reported [11–15]. In addition to optical applications, optical coatings draw interest for their applications in solar collectors and automotive or aeronautic components [16–18]. Plasma-sprayed metal coatings could provide excellent solutions in these fields. Some studies have been conducted on the optical properties of metal coatings, such as Al, Cu, and Ag. However, these optical coatings are typically prepared by chemical vapor deposition, physical vapor deposition (PVD), or sol–gel methods [19–21]. For example, an Ag thin film prepared by PVD does not only exhibit high reflectivity in the near-infrared and infrared ranges, it can also provide radiation protection [22].

Plasma-sprayed coatings have complicated microstructures, including multiscale, open and closed pores, and interfaces between particles and rough surfaces, which are very important in ensuring their radiative and optical properties. Studies on the optical behavior of transparent and heterogeneous materials have shown that reflectivity is not only related to the complex optical index of materials but to the heterogeneities, such as porosity, roughness, and grain size [23–25]. The optical properties of a particular material are mainly affected by roughness and porosity rather than grain boundary, which can be negligible when the porosity reaches a certain level [26]. In addition, for metal coatings, the possibility of oxidation or over-melting during plasma spraying may also significantly affect optical reflectivity. These problems and the microstructure of plasma-sprayed coating strongly depend on the molten state and the spreading degree of as-sprayed powders, which can be fully controlled by adjusting the plasma spraying parameters. Therefore, a precise control of plasma-sprayed parameters is required to overcome the difficult points of oxidation or over-melting of metal coatings. Meanwhile, it is worth mentioning that the plasma-sprayed Al, Cu, and Ag coatings have not been reported so far.

The current study primarily aims to systematically correlate the optical property of different metal plasma-sprayed coatings (Al, Cu, and Ag) with their microstructures, including phase, crystallinity, porosity, and surface roughness. The study also aims to discuss their corresponding mechanical properties.

2. Experimental

Commercially as-sprayed Al, Cu and Ag powders, prepared by alloy gas atomization technique, were provided by Forsman Scientific (Beijing) Co., Ltd. The morphologies and properties of Al, Cu, and Ag powders are shown in Fig. 1 and Table 1, respectively. The apparent density and flow velocity of as-sprayed powders were measured by using the FL4-1 funneled Hall flow meter (Central Iron & Steel Research Institute, China). Al powders appear as spherical and angular with a narrow size distribution ranging from 10 to 30 μm. Cu and Ag powders both appear spherical, with size distributions ranging from 50 to 80 μm and 40–70 μm, respectively. These powders with high flowability are appropriate for plasma spray technology. Low carbon steel of Φ25 × 10 mm was used as the substrate. Prior to deposition, the surface of substrates was ultrasonically cleaned with acetone and then grit-blasted using 24-mesh corundum grits. Plasma spraying was performed using an SG100 torch (Praxair, USA) under atmospheric pressure. As-sprayed powders were heated and accelerated in the plasma jet toward the substrate using Ar as the carrier gas. Mixtures of Ar-He were used as plasma gas and optimal plasma-sprayed parameters, as shown in Table 2. Commercial MCrAlY powders of Co-32Ni-21Cr-8Al-0.5Y (wt%, 20–80 μm) were provided by Praxair, United states. A MCrAlY metallic bond layer (between the substrate and metal coating) was deposited by high-velocity oxygen fuel spraying (HVOF) using a JP5000 torch (Praxair, USA), and the sprayed parameters are listed in Table 3.

Table 1
Properties of as-sprayed powders.

Sample	Melting temperature (°C)	Apparent density (g/cm^3)	Flow velocity (s/0.05 kg)
Al	660	1.9	42
Cu	1083	5.1	14
Ag	961	3.6	29

Porosity was measured using the Image J software (version 1.46r, USA) on the polished cross-section images of coatings obtained by scanning electron microscopy (SEM, HITACHI S4800, Japan). Ten images of each sample were taken from randomly selected areas to calculate the average porosity value. Surface roughness was measured with a portable roughness tester (TR100, Qulitest, USA). Roughness was calculated as the average of values measured at five different places. The bonding strength, defined as the average value of tensile bonding strength of three coating samples, was tested using the Multi-Specimen-Test Machine analysis system (WDW-1000, China) following GB/T 8642-2002. The geometry of the test fixture was Φ25 × 40 mm cylindrical mild steel. Two fixtures in pair were used and the coating sample was placed in the middle of them as shown in Fig. 2. Specimens for tensile bonding strength tests were bonded by using glue (Polyamide-epoxy FM-1000 adhesive film) and remained pressed against each other of test fixtures in a furnace set at 275 °C for 3 h. Microhardness measurement was conducted using the LM 700AT Vickers microhardness tester (LECO, Germany). A load of 100 g and a dwell time of 10 s were used. Average hardness was measured at five random locations on the polished cross-section of coatings. The crystalline structure of coatings was characterized with an X-ray diffractometer (XRD, X'Pert PRO MPD, Netherlands) using Cu Kα radiation, and then analyzed using JADE5.0 (Materials Data Inc., USA). The crystal size (D) of as-sprayed powders and coatings was calculated by the Scherrer's formula described in Eq. (1) [27],

$$D = {}^{0.94\lambda}\big/_{\beta\cos\theta} \tag{1}$$

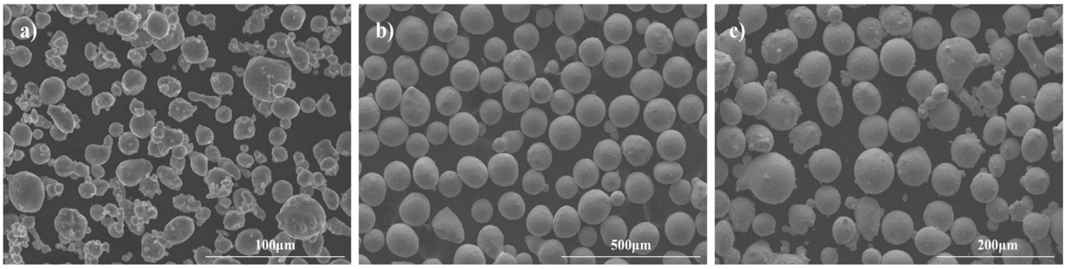

Fig. 1. Morphologies of the as-sprayed (a) Al, (b) Cu, and (c) Ag powders.