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Microstructure and magnetic properties of plasma-sprayed $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ coatings

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ABSTRACT

Amorphous and nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ coatings were formed by plasma-spraying micron-sized powders onto H62 brass substrates and aluminum pipes. The coatings are about 0.2–0.3 mm in thickness with fully dense and low porosity. The microstructure of the coatings is classified into two regions, namely, a full amorphous phase region and homogeneous dispersion of α-Fe nanoscale particles with a scale of 30–70 nm. The hardness of the amorphous and nanocrystalline coatings is about 960 HV_{100g}. Coercivity (Hc), saturation induction (B_{800}), and initial relative permeability (μ_i) of the coatings are 144 A/m, 0.27 T, 249, respectively, under 800 A/m direct current (DC) magnetic field. The magnetic shielding performance is good under DC magnetic field and its magnetic shielding effectiveness (SE) is 10–12 dB at coating thickness of 0.45 mm under static magnetic field of 2–40 Oe. The SE increases by increasing the coating thickness when the magnetic field frequencies are 50, 100 and 200 Hz with an intensity of 0.85 Oe. The results indicate that the amorphous and nanocrystalline alloy coatings can be good for some magnetic shielding applications.

1. Introduction

Amorphous and nanocrystalline materials have attracted significant interest due to their improved physical, magnetic and mechanical properties as compared to the conventional materials with micron-sized grains [1,2]. Especially, Fe-based amorphous and nanocrystalline alloys have considerable potential applications in industrial fields. However, the applications of these special alloys have been restricted due to the difficulties encountered in the production of bulk quantities and the limitations in thickness caused by rapid quenching methods such as melt spinning [3]. Currently the Fe-based amorphous alloy with very high glass forming ability has a critical diameter no more than 12 mm and meanwhile a small length [4].

Over the last few years, an important issue on forming amorphous or nanoscale structures in coatings is being developed. Thermal spraying process has been proven to be a successful technique for producing amorphous or nanostructured deposits [5,6], which could be used for some wear-resistant, corrosion-resistant applications. Fe–Si–B amorphous and nanocrystalline alloys have been extensively used as magnetic core materials in power and electronics field due to their excellent soft magnetic properties. Recently, thermally deposited Fe–Si–B alloy coatings have received much attention due to their good magnetic properties [7,8]. However, very few studies have been made on magnetic shielding properties of these coatings.

$Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy which has very good soft magnetic properties is one of the most commonly used alloys among Fe–Si–B alloys. The aim of this work is to produce $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ coatings from powders with micron scale size and analyze their microstructure and magnetic properties, particularly their magnetic shielding properties.

2. Experimental

Powders were made from $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ ribbons by machine grinder and airflow pulverization, and then sieved and divided into different size range. The powders with particle sizes in the range of 75–150 μm were used as feedstock powders.

Thermal spraying was carried out with a ZB-80 air plasma spraying system made by Surface Engineering Technology Institute of CAAMS (Chinese Academy of Agricultural Mechanization Sciences) onto H62 brass substrates with a thickness of 0.8 mm and aluminum pipes with

Table 1
Spraying parameters.

Primary gas flow rate	Ar 50 L/min
Auxiliary gas flow rate	H_2 22 L/min
Arc current	500–580 A
Arc voltage	60–70 V
Powder feed rate	50–70 g/min
Spray distance	120 mm

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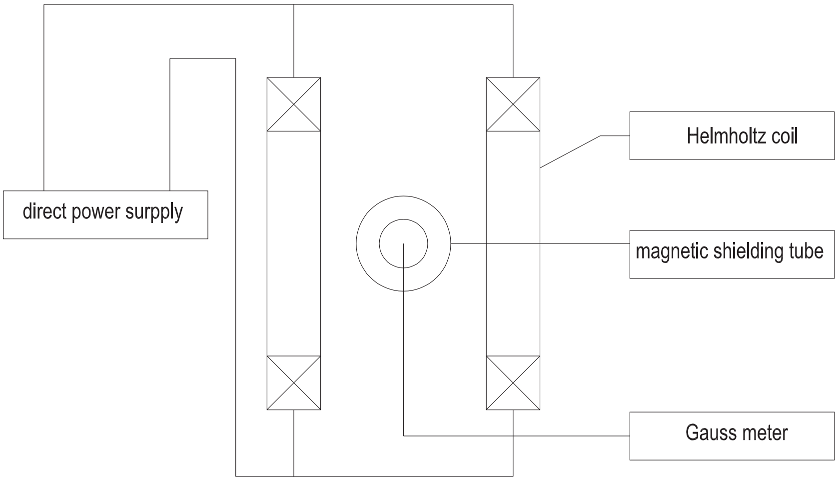

Fig. 1. Diagrammatic sketch of device for magnetic shielding effectiveness under DC magnetic field and low frequency magnetic field.

inner diameter of 36.1 mm, outer diameter of 38.2 mm and length of 200 mm. The thermal spraying parameters (Table 1) have been optimized to produce dense coatings.

The microstructures of the coatings were observed by using a JEOL JSM-6830LV SEM equipped with an energy dispersive X-ray analysis apparatus and TEM (Tecnai G2 F20). The phase structures in the coatings were determined by means of XRD with CuKα ($\lambda = 0.154$ nm) radiation on a D/Max-2400 apparatus. Coating microhardness was measured using a Vickers indenter with a 100 g load by means of a HXS-1000AK microhardness tester. The magnetic measurements were made with a MATS-2010SD DC hysterisismeter at ambient temperature. The magnetic shielding performance was measured using a lab-built measurement equipment (sketched in Fig. 1) under DC magnetic field and low frequency magnetic field of 50, 100 and 200 Hz. DC magnetic field and low frequency magnetic field with high uniformity in range of 1–100 G were produced by using Helmholtz coil of Model 9060 EM5 connected with direct power supply of KEITHLEY 2420 or functional signal generator of HP 33120A which can make alternative sinusoidal wave sign. Magnetic field intensity at the center of Helmholtz coil was determined using Gauss meter of Lakeshore 420, and H_0 is the value without magnetic shielding tube and H_1 is that with magnetic shielding tube (i.e. aluminum pipe sample with thermal spraying coating). The magnetic shielding effectiveness (SE) was determined by the formulation:

$$\mathrm{SE} = 20\lg\left(H_0 / H_1\right)\ (\mathrm{dB}).$$

3. Results and discussion

3.1. Microstructure

Fig. 2 presents the SEM image of the $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ feedstock powders with particle sizes in the range of 75–150 μm. All of the particles produced by airflow pulverization are obtusely polygonal, which is beneficial for plasma spray. The sizes of particles are relatively different between thickness direction of master ribbon and perpendicular direction.

The XRD diagram of pulverized particles and as-deposited coatings are shown in Fig. 3. Peaks above the amorphous background can be seen in both the powders and the coatings, indicating crystalline phases in the glass. Analysis of these peaks reveals that they are the phase α-Fe(Si). Since the little difference is found between them, the results suggest that the microstructure characteristics of the powders are maintained during spraying and impact on the substrate.

The SEM images of the coating on brass are shown in Fig. 4. The coating thickness is about 0.2–0.3 mm. From Fig. 4(A), the cross-section image of the coating, it can be seen that the coating is very dense, smooth, and with no cracking. Some limited porosities are visible as dark contrast regions. A typical lamellar structure of thermal spray is also detected. Less pores can be found from Fig. 4(B), the image of the polished surface, suggesting more dense in the same layer.

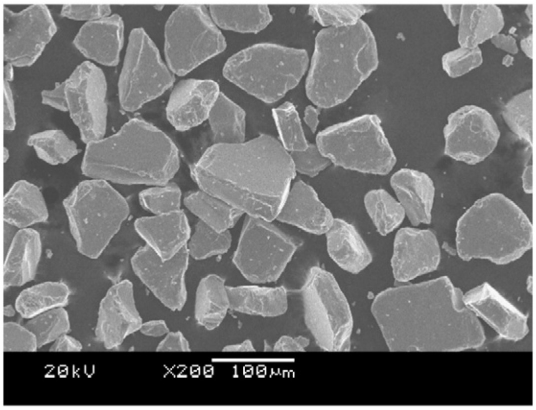

Fig. 2. A typical SEM image of $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ pulverized powders with size range of 75–150 μm.

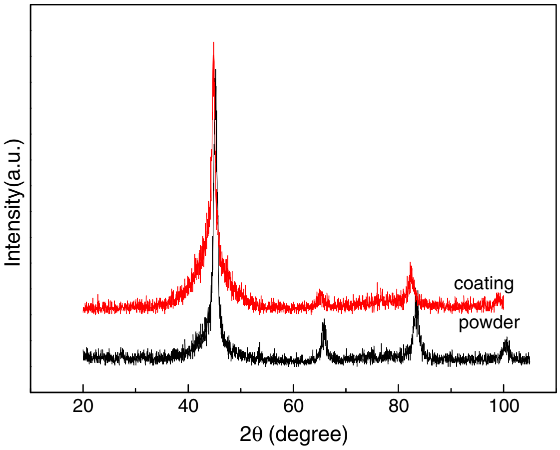

Fig. 3. XRD patterns of the airflow-pulverized powders and the as-deposited coatings for $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$.