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Iron boron based powders sprayed by high velocity spray processes

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ABSTRACT

In this work, a comparative evaluation has been carried out on the deposition efficiency of iron boride powder with a composition of Fe–17.9B–0.4C–1.6Si–0.3Al (wt.%) mixed with Ni powder (20 wt.%Ni) sprayed onto low carbon steel substrate by cold gas dynamic spray processes and the High Velocity Oxy-Fuel (HVOF) spraying method. The particle deformation and bonding mechanism were evaluated. Direct spraying of iron boride powders by low and high pressure cold gas spraying led to depositing a very thin single layer on the substrate, due to the intrinsic brittleness of the powder. Prior to spraying, reducing the particle size (−20 μm) and increasing the internal energy of the powders by the ball milling process resulted in no appreciable improvement in deposition efficiency, implying that sprayed particles still had insufficient ductility to plastically deform and flow. Likewise, iron boride powders were spray dried and sintered with Ni particles (FeB-20 wt.% Ni) to deposit layers in both low pressure and high pressure cold gas spray processes with various spray parameters. It was discovered that iron boride particles, surrounded by ductile Ni, experienced disintegration and cracking during deposition. The build up of iron boride layers was successfully obtained when spraying FeB20Ni powder by the HVOF deposition method. An abrasion wear test result of the HVOF coatings, 952 HV, was compared with HVOF sprayed WC-12Co coatings.

1. Introduction

It is well known that the conventional boriding process produces a hardened surface primarily composed of a polyphase boride layer (FeB and Fe_2B) [1]. However, the formation of the FeB layer is undesirable since it is very brittle and possesses a high thermal coefficient that leads to the development of thermal stresses during the heat cycle [2]. Therefore, to obtain reliable and anti-wear resistant coatings with borided layers, it is crucial to form only the single phase, preferably Fe_2B, during boriding [3]. Instead of forming hard iron boron layers with conventional boriding, which requires a relatively high amount of energy, and spraying directly the iron boron based powder with various compositions is promising due to the speed and ease of fabrication of the required surface specifications. The quick formation of boride layers produced by thermal spray methods including PTA boriding showed that the presence of the microcracks was generally unavoidable [4–6]. This is attributed to the cooling rate which leads to the generation of residual stresses, thus allowing for cracks in the coating. Cold gas spray (CS) is an emerging fast deposition technique that produces metallic coatings thanks to the relatively high plasticity of metal powder. The main attractive features of cold spray coatings are strong bonding with substrate, no phase transformation, i.e., retaining the original structure of feedstock, possible to obtain nano or ultrafine microstructure, almost no oxidation during spraying, and low heat input of the substrate which minimizes thermal damage [7–11]. Deposition of brittle materials makes the process particularly difficult due to the intrinsic inability to deform plastically. Therefore, the spraying of brittle materials remains a huge issue that has yet to be explored. There are few studies implementing the deposition of hard materials with a specially tailored structure suitable for CS. This is because hard particles normally break up when impinging on substrate, instead of undergoing plastic deformation. Therefore, the build-up of layers of hard materials by CS, their bonding mechanism with substrates having different hardness; and the structure of feedstock all need further investigation [12–15].

This paper reports the use of the CS process to form iron boron layers on metallic surfaces. Iron boron based powders (FeB) were sprayed onto low carbon steel substrate with low pressure (LP) and high pressure (HP) CS processes. Iron boride powder with nickel ductile powder produced by the spray drying method in different sizes was also cold sprayed onto steel substrate in order to understand the mechanism of brittle powder deposition. For a possible replacement coating of WC-12Co, which is more expensive than FeB based material (Table 1), spray dried FeB powder with Ni also was deposited by HVOF spray. Its resistance to abrasive wear was compared to the WC-12Co coating.

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Table 1
Typical properties of iron boride powders.

Properties	FeB	WC
Hardness	2400	1300–2200
Density(g/cm^3)	7.0	15.7
Crystal structure	Orthorhombic	Hexagonal
Melting point (°C)	1650	2800
Relative cost	1	3

2. Experimental procedures

The feedstock spray material of iron boron powders with a composition of Fe–17.9B–0.4C–1.6Si–0.3Al (wt.%) were supplied by Fujumi company (Fujumi Inc., Aichi, Japan).The morphology of the as-received powder (Fig. 1a) showed an irregular shape and wide particle size distribution ($d_{50} = 40$ μm), measured by a laser scattering particle size distribution analyzer (LA-910, Horiba, Japan). The iron boron powders deposited onto low carbon steel substrates (50 × 50 × 4t mm) followed by portable LP (Dymet model 403, OCPS, Russia) and stationary HP cold gas spray equipment (model PCS-203, Plasma Giken Co., Japan) with converging–diverging de Laval nozzle using air (for LP), and nitrogen, and helium (for HP) as impellent gas. Likewise, high velocity oxygen fuel (HVOF, JP500, Praxir/TAFA) spray method was also applied for comparison. Since the direct spraying of iron boron powders by LP, HP cold gas spray and HVOF processes failed, the iron boron powders mixed with ductile Ni, Fe and Al matrix materials with several content were prepared for spraying. Table 2 listed the details of the experimental studies and results of obtained coatings including the types of powders used, the spray methods followed, and post heat treatment applied. As seen from Table 2, spraying of iron boron powders was the first attempt to obtain iron boron coating layers. In order to achieve this, the as-received iron boron particles were sieved into −20 μm size ($d_{50} = 14$ μm) (Fig. 1b) and then subjected to high energy ball milling (Fig. 1c), which possibly facilitates the deposition owing to the increase in the internal energy of feedstock. Powders were milled by a laboratory scale high-energy ball milling unit of type Fritsch (Germany) within air atmosphere using various rotation speeds (ranging from 200 to 600 rpm) for a period of max 10 h milling. For the deposition of materials by the cold spray method, the spray particles must have sufficient ductility to plastically deform and flow and the substrate material must be hard enough to cause the incoming particle to plastically deform.

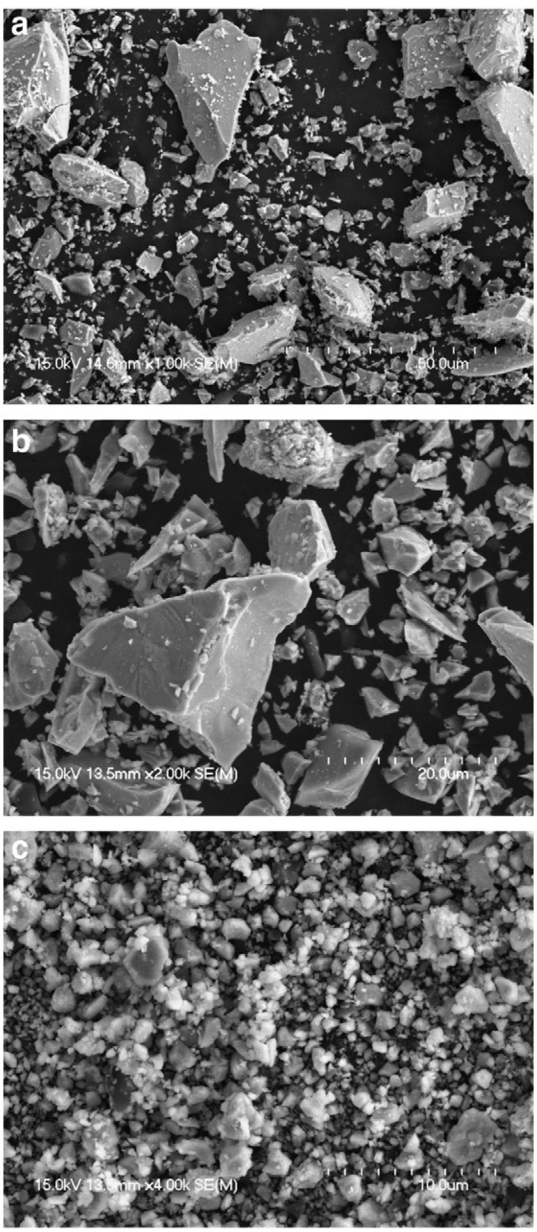

Fig. 1. SEM micrographs of feedstock FeB powder, a) as-received, b) sieved to −20 μm and c) ball milled for 10 h.

Secondly, the sieved fine iron boride powders mixed with 20 wt.% Fe (FeB20Fe) and Ni powder (FeB20Ni) the composite powders (d_{FeB} 20 μm, and $d_{50Fe,Ni} = 2$ μm) were prepared by a spray-drying and post-sintering method. The typical appearance of agglomerated-sintered powders and cross section microstructure were shown in Fig. 2. Additionally, in order to scrutinize the ductile phase effect on deposition behavior of such brittle powder, both types of sintered composite powders were mixed with 10 wt.% pure aluminum powder (FeB20Ni10Al and FeB20Fe10Al) and subsequently subjected to the ball milling operation (see Fig. 3a–b).

In order to reduce the overall porosity of resultant coatings and improve the adhesion of the layers deposited, an isothermal post heat treatment was carried out in a vacuum assisted furnace (approx. 10^{-2} Pa) for 1 h, up to 700 °C. Differential scanning calorimetry (DSC, Netzsch STA 409 C) was employed to determine possible formation of hard phases in iron boron based composite powders. The powders were scanned between 20 °C and 1000 °C at 10 K/min in an argon atmosphere.

To characterize the spray powders and coatings an X-ray (XRD; M21X, MAC Science Co. Ltd., Japan) using CuKα radiation, a scanning electron microscope (SEM, Hitachi FE-SEM S-4700) equipped with energy dispersive X-ray (EDX) analysis, and transmission electron microscopy (TEM) using a field emission transmission electron microscope (Jeol JEM 2100 F, Japan) operating at 200 kV were used. The Vickers micro-hardness (HV) of coating was measured by a computer-controlled measuring system (Fischerscope HM2000 XYp, Germany). Suga abrasion test (ASTM D6037) was conducted to investigate abrasive wear resistance of the iron boron coatings, where abrasive paper of SiC F180 was used as a counter material under 3.15 kgf (30.9 N) loading. The reciprocating velocity and wear area were 40DS/min and 30 × 12 mm, respectively. HVOF sprayed WC-12Co coating, which carbide particle and feedstock particle size were 2 μm and −45 + 15 μm, respectively, was also wear tested in order to make a comparison. Further details of HVOF spray and Suga wear test conditions were given elsewhere [16].

3. Results and discussion

3.1. Deposition of hard FeB particles by cold and HVOF spray processes

The cold gas spraying of iron boride powders deserves special attention due to the specific properties given in Table 1. FeB powder is