Effects of Oxygen Fuel Rate on Microstructure and Wear Properties of Detonation Sprayed Iron-Based Amorphous Coatings

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The Fe-based (iron-based) amorphous coatings were prepared by detonation spray at various oxygen fuel rates. The microstructure and wear properties were examined. The amorphous phase contents of coatings were calculated to be 89.73%, 86.23% and 81.46%, respectively, which were higher than those fabricated by other thermal spray techniques. The porosity was tested to be 2.1%, 1.4% and 0.8%, respectively. The wear resistance of Fe-based amorphous coatings was four times better than the stainless steel substrate. The oxygen fuel rate of 1.2 m³/h~1.0 m³/h was proved to be the optimal parameter of fabricating Fe-based amorphous coating. The effects of oxygen fuel rate were discussed. [doi:10.2320/matertrans.M2018273]

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1. Introduction

During the past few years, Fe-based amorphous alloys have attracted much attention for their outstanding properties, such as high strength, high hardness, good corrosion and wear resistance, as well as the relative low cost.¹–⁸ However, the application of amorphous alloys was restricted in industrial field due to the limited product size, poor plastic deformation and no work hardening at room temperature.

Recently, Fe-based amorphous coatings as an alternative form of Fe-based amorphous alloys, have been focused on because they can abandon the shortcomings of the alloys above, and also maintain the preeminent wear and corrosion resistance.⁹–¹³

Thermal spray techniques are suitable for prepare Fe-based amorphous coatings due to the high working temperature and particle flying speed,¹⁴–¹⁷ which are beneficial for the forming of amorphous phase. Many researchers applied thermal spray to make Fe-based amorphous coatings. Masahiro Komaki et al.¹⁸ used gas flame spray to fabricate Fe₇₀Cr₁₅P₆₇C₉₆amorphous coating, and examined the microstructure and corrosion resistance. Zhenhua Chu et al.¹⁹ applied gas multiple-tunnel plasma spraying to make Fe₅₁.3₃Cr₁₄.9Mo₂₅.₆₇Y₃.₄₄C₃.₄₄B₁.₂₆ amorphous coating, and discussed the effects of ZrO₂ on the wear resistance. Piao Zhong-yu et al.²⁰ adopted supersonic plasma spraying to prepare Fe₅₁CrMoBC amorphous coating with addition of ZrO₂, and discussed the effects of ZrO₂ on the wear resistance. Zhou et al.²¹ attempted to make Fe₄₈Cr₁₃Mo₁₄C₁₂B₅Y₂ amorphous coating by detonation spray and examined the microstructure and electro chemical corrosion resistance. They found the coating possessed an amorphous content of 54%, and showed good corrosion resistance in the solutions of 3.5% NaCl and 1 mol/L HCl. Wu et al.²² used detonation spray to prepare Fe₃₁₃₃Cr₄₄.₈Mo₂₅.₆₇Y₃.₄₄C₃.₄₄B₁.₂₆ amorphous coating, found the coating possessed an amorphous content of 85% and a porosity of 2.1%, and studied the wear behavior. However, the attempts of applying detonation spray to make Fe-based amorphous coatings are not enough, and no report is found focused on effects of oxygen fuel rate which is the key parameter to influence the microstructure and wear properties of coatings. The objective of this work is to fabricate high quality Fe-based amorphous coatings by detonation spray, and discuss the effects of oxygen fuel rate on microstructure and wear properties.

2. Experimental Procedure

Commercially available Fe-based amorphous powders with a size of about 40–75 µm were prepared by gas atomization. The composition and SEM micrograph are listed in Table 1 and Fig. 1. The 304 stainless steel plates with a dimension of 150 mm × 50 mm × 4 mm were selected as the substrates. All the substrates were smoothed with a grinder machine first, then cleaned with acetone and dried in air, and ultimately grit-blasted prior to deposition. The coatings were prepared by detonation spraying equipment (Dnepr-III, Ukraine). The detailed spray parameters are listed in Table 2.

The morphologies of the spray powder and coatings were characterized by scanning electron microscopy (SEM, TESCAN) equipped with energy dispersive spectroscopy (EDS). The microstructure of powder and coatings was examined by X-ray diffraction (Rigaku D/max−2550VB diffractometer (Cu Kα radiation)) and transmission electron microscopy.

<p>| Table 1 Composition of the spray powder. |</p>
<table>
<thead>
<tr>
<th>Composition</th>
<th>Mo</th>
<th>Cr</th>
<th>C</th>
<th>Si</th>
<th>B</th>
<th>Ni</th>
<th>Y</th>
<th>Mn</th>
<th>Cu</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content (%)</td>
<td>22.5</td>
<td>15.1</td>
<td>3.30</td>
<td>1.92</td>
<td>1.12</td>
<td>1.12</td>
<td>0.34</td>
<td>0.28</td>
<td>0.15</td>
<td>BAL</td>
</tr>
</tbody>
</table>

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microscopy (Tecnai G2 20S-Twin, FEI). The porosity of the coatings was evaluated by analyzing SEM micrographs with the Image Pro-Plus 6.0 software. At least fifteen cross-sectional SEM images at the magnification of 1000 times were randomly selected for the porosity measurement of each coating. Microhardness of the coatings was examined on polished cross sections by using a Vickers microhardness indenter (HX-1000, Shanghai Second Optical Instrument Factory, China) under a 300 g load for duration of 15 s. Twenty measurements for each coating were obtained and the average value was calculated, as well as the standard deviation. Friction and wear experiments were conducted under dry condition using a ball-on-disk sliding apparatus (CERT UMT-3, USA) at room temperature. Chromium steel balls with a diameter of 9.525 mm, a hardness of 50HRC and a mean surface roughness of around 50 nm were used as the counterpart material. New ball was used for each test. Before the wear test, all samples were grinded, polished and cleaned. The total sliding distance was 500 m, the load was 20 N, and the sliding velocity was 0.1 m/s, 0.2 m/s, and 0.3 m/s for each specimen. The wear rate $W$s of the coating can be estimated by the equation of $W_s = V/DL$ where $V$ is the volume loss, $D$ the sliding distance, and $L$ is the load applied on the specimen. The volume loss $V = m/\rho$, where $\rho$ is the density of the coating material, $m$ is the mass loss measured after each test run. The worn surfaces of substrate and coatings were characterized by SEM.

3. Results and Discussion

3.1 Structure characterization and morphology

Figure 2 exhibits the XRD patterns of the spray powder and the coatings which were prepared by detonation spray with different oxygen fuel rate. All the coatings display a broad diffraction hump approximately $2\theta = 40^\circ$–$50^\circ$. Several crystalline diffraction peaks can be observed. This result reveals the coatings are mainly composed of amorphous phase. The main crystalline phases in the coating comprise $M_23C_6$ and $\alpha$-Fe solid solution. The amorphous phase content calculated by MDI Jade 5.0 in C1, C2 and C3 was 89.73%, 86.23% and 81.46% respectively, and these values were higher than those in the coatings fabricated by other thermal spray techniques (Plasma spray, 69.33%;22 AC-HAVF, 81.25%;11 HVOF, 74.9%;10). The difference can be due to the heat produced at different oxygen fuel rate during the spray process. When the oxygen fuel rate increases, the heat transferred to powders increases.23) So, the powders impacted by higher oxygen fuel rate form the coating heated more strongly and results in decreasing the amorphous phase content of the coating by crystallization induced by residual heat. The microhardness of C1, C2 and C3 was tested to be HV0.31300 «47, HV0.31200 «55, HV0.31050 «62. The variation tendency of microhardness accords with the amorphous content of coatings. It can be due to the super high hardness of amorphous phase.

Figure 3 shows the cross sectional morphologies of C1, C2 and C3. Numerous pores and cracks can be seen in C1 as well as several unmelted particles. The typical lamella structure of thermal spray coatings can be found in C1. Much less pores and cracks are observed in C2, and unmelted particles can be not almost found. The typical lamella structure decreases. C3 exhibits the densest morphology among the coatings. Obvious crack can be not found in the least. The typical lamella structure disappears. The porosity calculated by Image 6.0 in coatings of C1, C2 and C3 was 2.1%, 1.4% and 0.8%, respectively. This can be explained that higher oxygen fuel rate produces higher kinetic energy and heat.16) The higher kinetic energy can strengthen the
bonding of the particles and decrease the pores and cracks; the higher heat can fully melt the powders and reduce the unmelted particles.

3.2 Wear properties of the coatings and stainless steel substrate

Figure 4 shows the SEM picture on friction surface of the coatings and stainless steel substrate. From Fig. 4(a), many scratches and granules can be seen on the friction surface of steel. This can be ascribed to the low hardness of steel. During the wear process, the materials with low hardness will be easily abraded away. Moreover, the counterpart can be prone to press into the steel, then the scratches form. From Fig. 4(b), fracture and peeling morphology can be found on friction surface of C1. This characteristic is caused by periodic friction force during the wear process. From Fig. 4(c), few fracture, peeling and wear pits morphologies are found on the friction surface of C2. The surface is smooth. From Fig. 4(d), big wear pits can be found on the friction surface of C3. The wear pits can be explained that the microhardness of C3 is lower than C1 and C2, hence, an amount of the materials on the surface will be abraded away, and then the pits form.

Figure 5 displays the wear rate of the coatings and stainless steel substrate. It can be seen that the wear rate of coatings is much lower than the stainless steel substrate, which means the wear resistance of the detonation sprayed Fe-based amorphous coatings is at least four times better than stainless steel substrate according to the wear rate value. So it will significantly increase the service life of the stainless steel substrate by depositing Fe-based amorphous coating with detonation spray technique. The wear rate of C2 is the lowest among the coatings, which means C2 shows the strongest wear resistance. As sliding velocity increases, the wear rate increases.

The difference between wear properties of the coatings can be ascribed to the microhardness and porosity. When microhardness is high or porosity is low, the wear resistance is improved. The microhardness of the coatings is ranked as C1 > C2 > C3, and the porosity is ranked as C1 > C2 > C3. Therefore, C2 obtains the best wear properties which depend on both the microhardness and porosity. Moreover, C1 exhibits better wear properties than C3, which indicates that the microhardness is more important parameter against wear property than the porosity when the porosity of the coatings is in the very low stage.

4. Conclusions

FeCrMoYBSiCNiCuMn amorphous coatings were prepared by detonation spray under three different conditions of oxygen fuel rate which are 1.0 m³/h~1.0 m³/h (sample C1), 1.2 m³/h~1.0 m³/h (sample C2) and 1.5 m³/h~1.0 m³/h (sample C3). The microstructure, microhardness, porosity and wear properties of the coatings were examined. The following conclusions are drawn from the present work:

1) The higher oxygen fuel rate is, the lower amorphous phase content is. It’s due to the crystallization by higher
heat. The amorphous phase content of C1, C2 and C3 were examined to be 89.73%, 86.23% and 81.46%, respectively, higher than those fabricated by other thermal spray techniques;

(2) The higher oxygen fuel rate is, the lower porosity is. It’s ascribed to the melting degree of powders by the higher heat and kinetic energy. The porosity of C1, C2 and C3 is 2.1%, 1.4% and 0.8%, respectively.

(3) The friction surface of C1 exhibits fracture and peeling morphologies, C2 shows few peeling and wear pits morphologies, C3 displays wear pits morphologies. It is due to the difference in microhardness and porosity of each coating;

(4) The wear rate of the amorphous coatings is at least four times lower than stainless steel substrate, which indicates extension of the service life of substrate. The C2 exhibits the lowest wear rate. It is due to the difference in microhardness and porosity of each coating.

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