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Tribological properties of $FeCoCrNiAlB_x$ high-entropy alloys coating prepared by laser cladding

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ABSTRACT

$FeCoCrNiAlB_x$ (x = 0, 0.25, 0.50, 0.75) coatings were prepared by laser cladding to study the effects of boron on the structure and properties of high-entropy alloys coatings. The microstructure, microhardness, and wear resistance properties of the samples were investigated by scanning electron microscopy, X-ray diffraction, metallographic micro-hardness test, and friction-wear test, respectively, and the mechanism of the wear behavior was also analyzed. The results showed that the high-entropy alloys consisted of BCC phase and eutectic structure, which contained FCC phase and M_2B. With boron addition, the content of BCC phase increased while that of eutectic structure decreased. The wear resistance of the high-entropy coatings was considerably improved with increasing addition of boron, and accordingly, the $FeCoCrNiAlB_{0.75}$ coating showed the best wear resistance.

1. Introduction

According to some traditional views, various intermetallic compounds and other complicated phases would exist in one alloy system if it contains many kinds of components, which not only decreases the properties of the alloy, but also makes it difficult to analyze[1-3]. Yeh et al.[4-6] proposed a new route for alloy design, making a breakthrough from the traditional way. A kind of high-entropy alloys consists of at least five principal components and the atomic ratio of each component should be 5%—35%. Thus, the properties of the high-entropy alloys, which were made by them with multiple principal components, depend on the properties of the new alloy system composed of those components. It was found that a solid solution with high stability against heating, nanostructures, and even non-crystalline structure, can be gained in high-entropy alloys because of the high entropy and the characteristic of restricting atomic diffusion. Non-crystalline material has many excellent properties such as wear resistance, corrosion resistance, and high microhardness, which have made it a focus of research since the 1980s. To some extent, high-entropy alloys show almost the same properties as non-crystalline material[7]. Li et al.[8] found that the addition of Al could cause a transformation from an FCC structure into a BCC structure of the high-entropy alloys, which improved the corrosion resistance of $FeCoNiCrCu_{0.5}Al_x$ alloy after electric arc melting. It was also found that the Ni addition would affect the thickness and ductility of an $Al_2CrFeCoCuTiNi_x$ high-entropy alloys coating produced by laser cladding[9]. Besides, similar studies showed that the addition of boron could increase the hardness and wear resistance of $CuCoNiCrAl_{0.5}Fe$[10]. However, high-entropy alloys are still under investigation and many precise measurements are required to explain the lattice distortion effect. The properties of high-entropy alloys are superior to those of traditional alloy in many ways, such as hardness, thermal stability, wear resistance, and self-healing ability under irradiation[11-13], and those excellent properties mean that wide applications have been proposed for high-entropy alloys in the field of engineering materials, especially for producing high-performance anti-wear coatings[14].

Laser cladding has many advantages, such as high velocity of heating and cooling, strong adhesion with the substrate, a small heat affected zone, very little change of shape, and thickness of coatings that reaches millimeter level. The fast solidification of

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laser cladding can cause an effect of solute trapping, which helps avoid composition segregation and increases the solid solubility of coatings[15]. Ocelík et al.[16] found that the solidification rate plays an important role in the composition and distribution of phases in alloy during the procedure of compositing FeCoCrNiAl using laser cladding. A high solidification rate can increase the content of BCC phase, which changes the hardness. In conclusion, depositing high-entropy alloys coatings with laser cladding could give them excellent mechanical properties.

In this study, laser cladding was used to deposit $FeCoCrNiAlB_x$ (x means the molar ratio of boron, which should be taken as 1 unless otherwise specified) high-entropy alloys coatings on Q235 steel, and the effect of boron addition on microstructure and wear resistance of $FeCoCrNiAlB_x$ high-entropy alloys was discussed.

2. Experimental

High purity Fe, Co, Cr, Ni, Al, and boron powders, which were mixed according to the molar ratio of $FeCoCrNiAlB_x$ ($x=0$, 0.25, 0.50, 0.75) and with average particle size of 50 μm, were chosen for laser cladding, and Q235 steel cleaned by acetone was chosen as the substrate. The powder mixture was put in a planetary ball mill and mixed for about 10 h, and then spread on the surface of Q235 substrate with a thickness of 1.5 mm. The operation parameters were as follows: power $P=500$ W, scanning velocity $v=3$ mm/s, and spot diameter $D=4$ mm. The microstructure of the high-entropy alloys was observed by scanning electron microscopy (S3400, Hitachi, Japan) and the coating components were analyzed using X-ray diffraction (XRD, Shimadzu 7000, Japan) with CuKα ($\lambda=0.154$ nm) radiation at a step of 0.02°. The microhardness was tested using a Vickers hardness tester (HVS-5) with a load of 0.2 N and loading time of 10 s; ten points were measured and then the average hardness was calculated. The wear resistance was tested on a pin-on-disk wear testing machine (MMW-1 Universal Wear Testing Machine) with a disk made of Cr12MoV as the counterpart. The wear test lasted for 15 min with a load of 100 N and a rotation speed of 100 r/min.

3. Results and Discussion

3.1. Macro-morphology

The macro-morphology of $FeCoCrNiAlB_x$ is shown in Fig. 1. The addition of boron showed no significant effect on the macro-morphology of cladding layers. It can be seen that no cracks or pores exist in the cladding layer. Table 1 shows the elemental analysis of the cladding layer surface. The Fe content was a little higher than those of other elements because the Q235 steel was used as the substrate of the cladding layer, and Fe was mixed into the layer during the cladding procedure.

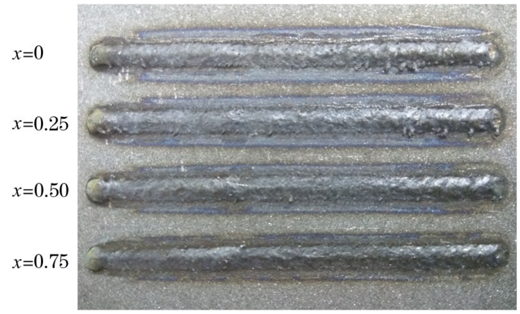

Fig. 1. Macro-morphology of the cladding layer.

Table 1
Elemental analysis of the cladding layer surface

Fe	Co	Cr	Ni	Al	B
36.04	15.05	20.26	14.67	9.47	4.51

3.2. X-ray diffraction

Fig. 2 shows the diffraction peaks of coatings with different compositions, which indicated that the $FeCoCrNiAlB_x$ high-entropy alloys consist of BCC and FCC (mostly Fe) structures and M_2B (M is mainly represented by Fe, Co, Cr, and Ni). There were only a few kinds of intermetallic compounds existing in the $FeCoCrNiAlB_x$ high-entropy alloys due to the inhibiting effect of the high entropy[17].

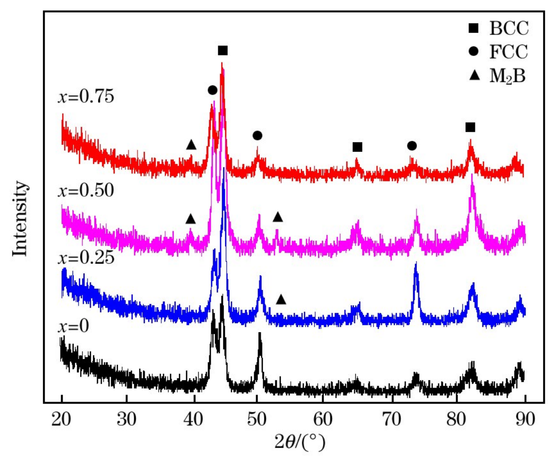

Fig. 2. XRD results for cladding coatings.

The Gibbs free energy of mixing was defined as follows:

$$\Delta G_{mix}=\Delta H_{mix}-T\Delta S_{mix} \tag{1}$$

This formula describes the relationship of Gibbs free energy (ΔG_{mix}), enthalpy (ΔH_{mix}), and mixing entropy (ΔS_{mix}) of the disordered solid solution. The mixing enthalpy of the system can be expressed by the Boltzmann approximation as follows: