Superior Slurry Erosion Behavior of a Casting NiCoCrFeNb_{0.45} Eutectic High Entropy Alloy

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Abstract

The flow passage components in hydraulic machinery will be eroded rapidly when running in sand water. The wear resistance of materials commonly used in hydraulic machinery needs to be improved to prevent the failure of hydraulic machinery. New wear-resistant materials are urgently needed to improve the service life of hydraulic machinery. Eutectic high entropy alloy (EHEA) is a new kind of alloys with in situ lamellar structure. NiCoCrFeNb_{0.45} EHEA has combined excellent strength and toughness. In this study, slurry erosion tests of NiCoCrFeNb_{0.45} EHEA were carried out with different impact angles and impact velocities using a rotary jet erosion test apparatus. The NiCoCrFeNb_{0.45} EHEA exhibited significant slurry erosion resistance compared with medium carbon steel 1045 and stainless steel 04Cr13Ni5Mo. The erosion rate of EHEA is much slower. Compared with medium carbon steel and stainless steel, the erosion of EHEA is completed via the accumulation and removal of platelets after plowing and work hardening, accompanied by partial micro-cutting.

Keywords Eutectic high entropy alloy · Friction and wear · Slurry erosion

1 Introduction

In hydraulic machinery, slurry erosion is one of the main reasons for material damage and equipment failure. In the area with high sediment content, slurry erosion of water conservancy and hydropower facilities is very severe under the action of liquid–solid two-phase flow [1–3]. At present, components used in hydraulic machinery such as water turbines and valves are mostly made of stainless steel. Martensitic stainless steel 04Cr13Ni5Mo with better abrasion resistance has been widely used in the manufacture of hydraulic machinery, including impellers and blades. However, it remains unsatisfied in some extreme circumstances. Moreover, the effort and cost to repair or replace [4, 5] the

impellers and blades are extremely huge. Therefore, it has always been the dream of hydro-engineers to have an alternative material with better resistance to abrasion.

Slurry erosion refers to the surface removal caused by the impact of flowing particles on a material. The material with higher hardness and toughness will show a better performance. The recently developed high entropy alloys (HEAs) have a great chance to improve slurry erosion resistance. HEA was been proposed by Yeh et al. [6] with several principal elements where the content of each element is between 5 and 35% [7]. In other words, this kind of alloys is formed by the collective action of a variety of elements, thus showing different characteristics from traditional alloys. However, the single-phase high entropy alloys have some mechanical defects. The single-phase CoCrFeMnNi HEA has good toughness and plastic deformation ability, but its strength is far from engineering applications. Nair et al. [8] reported that the toughness of FCC single-phase Al_{0.1}CoCrFeNi HEA is better than SS 316L, but the slurry erosion rate for it is slightly higher compared to SS 316L stainless steel because of its lower hardness. The BCC single-phase HEA, represented by VNbMoTaW alloy, has excellent mechanical properties, but its toughness is limited. Therefore, the idea of using composite materials to balance the strength and the toughness of HEAs was proposed [9]. The eutectic alloy

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is a kind of in situ composite with regular lamellar or rod-like structure formed spontaneously during solidification. In eutectic high entropy alloy (EHEA), if the lamellar eutectic structure is composed of the phase with high hardness and the phase with good toughness, the slurry erosion resistance will be greatly enhanced. Zhao et al. [10] reported that the $\text{Al}_{1.0}\text{CoCrFeNiTi}_{0.5}$ HEA is composed of simple FCC phase and BCC phase, and its erosion rate is 1.73 times lower than Cr16 alloy. Wu et al. [11] reported that with the increase in the aluminum content in $\text{Al}_x\text{CoCrCuFeNi}$ alloys, both the BCC phase proportion and the hardness value increase. However, the wear coefficient decreases and the wear mechanism changes to oxidative wear. Chuang et al. [12] observed that $\text{Co}_{1.5}\text{CrFeNi}_{1.5}\text{Ti}$ and $\text{Al}_{0.2}\text{Co}_{1.5}\text{CrFeNi}_{1.5}\text{Ti}$ have higher oxidation resistance and lower high-temperature softening, indicating that they have excellent wear resistance compared to conventional alloys. Hsu et al. [13] reported that the wear resistance and high-temperature compressive strength of $\text{Al}_{0.5}\text{CoCrCuFeNiB}_x$ were increased due to the addition of boron content and the formation of borides.

$\text{NiCoCrFeNb}_{0.45}$ is a eutectic high entropy alloy composed of the FCC phase and Laves phase, exhibiting excellent strength and toughness [14, 15]. The Laves phase is much harder than the ordered BCC phase. Therefore, it is believed that $\text{NiCoCrFeNb}_{0.45}$ will show better performance in the slurry erosion resistance, due to its excellent combination of strength and toughness. Here, we investigated its slurry erosion performance by using rotating erosion apparatus in simulated conditions of liquid–solid two-phase flow. Compared with the current hydraulic machinery materials, the erosion wear resistance of EHEAs exhibited a superior performance. The corrosion resistance mechanism of EHEA was also discussed.

2 Experimental

2.1 Materials

The EHEA samples with the nominal composition of $\text{NiCoCrFeNb}_{0.45}$ were prepared by arc melting and copper mold casting, respectively. Elements of Co, Cr, Fe, Ni and Nb with purity of 99.95% were used as raw materials. The alloys were melted with electromagnetic stirring for five times to ensure the homogeneity and then solidified in a water-cooled copper hearth [16]. $\text{NiCoCrFeNb}_{0.45}$ EHEA, medium carbon steel 1045 (MCS) and stainless steel 04Cr13Ni5Mo (SS) commonly used in hydraulic machinery were made into 44 mm × 12 mm × 6 mm samples. To avoid the impact of surface roughness on the erosion test, the samples were successively polished with 240#, 400#, 800#, 1200#, 1500# and 2000# SiC sandpapers. The samples were subsequently polished with polishing cloth and finally put into alcohol for ultrasonic cleaning. Sand particles in the size range of 100–200 μm were used for the slurry erosion studies.

2.2 Slurry Erosion Test Apparatus

The rotary jet erosion test apparatus is a circulating test device as shown in Fig. 1. The samples are fixed along the circumferential direction on the turntable that is driven by a drive motor, and the fluid is injected on the turntable through four uniformly distributed nozzles on the front cover of the turntable room. The mixing device in the mixing tank prevents particles from settling and maintains a uniform mixture of the particles and the fluid. The surge tank provides a steady injection of fluid, and the cooling system keeps the fluid temperature constant throughout the test process. The parameters of the experimental apparatus, including impact

Fig. 1 Schematic view of the slurry erosion test apparatus used in the experiment

angle, impact velocity and jet distance can be changed freely for implementing flexible tests.

2.3 Slurry Erosion Test

The actual operating environment of hydraulic machinery was simulated in the experiment. Slurry erosion tests were carried out on MCS, SS and EHEA using the rotary jet erosion test apparatus. Slurry erosion experiments in our work were performed according to the ASTM-G73 standard that was also applied in [17–19]. Table 1 gives the parameters of the erosion test. The impact velocity and impact angle can be varied by changing the flow rate and the rotating speed of the rotary plate. Different combinations of the flow rate and rotation speed of 20 m/s 30°, 25 m/s 30° and 25 m/s 20° were applied. The water mixed with quartz sand was selected to simulate the actual river flow. In the erosion process, the sand was changed periodically to ensure the geometric shape of the sand for consistency. In the test, all the samples were taken out, cleaned with ethanol and checked every 3 h. After the cleaning and drying, the mass was measured with an electronic balance with a precision of 0.1 mg. The average value was calculated using the three weighing results. The normalized mass loss of samples was calculated using the following formula:

$$\varepsilon = \Delta m / S.$$

Table 1 Test parameters used for slurry erosion

Parameters (Unit)	Value
Temperature (°C)	25
Impact velocity (m/s)	20, 25
Erosion time (h)	12
Nozzle diameter (mm)	2.5
Impact angle (°)	20, 30
Particle (μm)	100–200
Stand-off distance (mm)	12

where ε is the mass loss of samples, Δm is the mass difference of the samples before and after tests and S is the sample surface area.

After the test, optical microscope (OM) and scanning electron microscope (SEM) were used to characterize the surface morphology of samples. The microstructures were obtained approximately 152 mm away from the center of the turntable. The erosion resistance of the three materials was compared, and the erosion mechanism of EHEA was analyzed.

3 Results and Discussion

3.1 Microstructural and Mechanical Characterizations

The microstructures of EHEA, MCS and SS are shown in Fig. 2. The microstructure of MCS 1045 is medium flake pearlite with a small amount of ferrite and flake graphite. Ferrite and flake graphite are soft and have low hardness (Table 2). SS 04Cr13Ni5Mo belongs to ultra-low carbon martensite stainless steel, composed of lath-like martensite, reversed austenite and granular carbide. The hardness and toughness of SS are relatively good. EHEA exhibited a hypoeutectic microstructure with a high proportion of eutectic lamellar structure. The eutectic lamellar structure was composed of FCC/Laves dual-phase constitution. The microhardness of EHEA, MCS and SS is listed in Table 2.

3.2 Slurry Erosion

Figure 3 shows the erosion results of all the tested samples under different conditions. Comparing Fig. 3a with

Table 2 Hardness of EHEA NiCoCrFeNb_{0.45}, SS 04Cr13Ni5Mo and MCS 1045

Material	Hardness (Hv)
EHEA	522
SS	201
MCS	181

Fig. 2 Microstructures of **a** MCS 1045, **b** SS 04Cr13Ni5Mo **c** NiCoCrFeNb_{0.45} EHEA

Fig. 3b, it can be found that the erosion increases at a higher velocity. This is because the increase in impact velocity improves the kinetic energy of sand particles and the amount of sand particles shooting on the sample surface per unit time. Comparing Fig. 3b with Fig. 3c, the erosion reduces with the decrease in impact angle, which indicates that the ablation is determined by the head-on shock and cutting. Under all the test conditions, the EHEA exhibits the best performance in terms of erosion resistance. In the most severe environment, the erosion mass loss of EHEA is one magnitude lower than that of the MCS and a third of that of SS. The effects of the impact angle and velocity on the erosion in sand water flow are summarized in Fig. 3d. It is shown that the EHEA is a promising candidate for hydraulic metallic materials.

EHEA showing a super anti-erosion performance is related to its FCC/Laves dual-phase constitution with uniform and fine lamellar microstructure. The eutectic lamellar microstructure with soft FCC and hard Laves phase achieves

an excellent balance between high strength and high ductility. High toughness can improve the abrasion performance of materials, and high hardness increases the fracture strength of materials. Therefore, more sand impact is needed to remove materials on the surface [20–23]. Moreover, EHEA makes up for the previous shortcomings in the performance of single-phase HEA. The existence of hard Laves phase effectively improves the hardness. Additionally, the lamellar spacing of EHEA alloy was measured as about 200 nm and the smaller value of lamellar spacing would produce a higher hardness and strength. Hardness is a dominant mechanical property that modulates the erosion rates for a given class of materials [24]. Therefore, EHEA with high hardness and toughness makes its erosion loss much lower than that of MCS.

3.3 Erosion Mechanism

The SEM images of the eroded surface morphology are shown in Fig. 4. These images show that micro-cutting and plowing

Fig. 3 Variation in the erosion of MCS 1045, SS 04Cr13Ni5Mo and NiCoCrFeNb_{0.45} EHEA with erosion time: **a** at impact speed of 20 m/s and impact angle of 30°, **b** at impact speed of 30 m/s and impact angle of 30°, **c** at impact speed of 25 m/s and impact angle of 20° **d** Cumulative mass loss as the function of impact angle and impact speed

are two main abrasion mechanisms that cause material removal. Severe micro-cutting and plowing marks were observed on the surface of SS and EHEA samples, respectively. Micro-cutting is the main erosion mechanism of SS (Fig. 4a, c). However, for EHEA, plowing is the most common erosion mechanism (Fig. 4b, d). Compared with SS exhibiting large peeling indent on the surface (Fig. 4c), EHEA has a large number of lips, severely deformed platelets and only micro-indent.

The difference of main erosion mechanism between EHEA and SS may be related to their difference in toughness and hardness. For high ductile materials, the main erosion mechanism of materials is the platelet mechanism, which is independent of the impact angle [25]. Higher toughness helps the platelets that are re-impacted to withstand a greater degree of deformation than less ductile materials. Therefore, a large number of severely deformed platelets can be observed on the surface of EHEA after erosion test (Fig. 4d). In contrast, the wear surface of SS is mainly covered by micro-cutting marks. For EHEA, the formation and removal of platelets are the main mode of material loss. The deformed structures removed by micro-cutting and plowing on the material surface are attached to the surface in the form of platelet (Fig. 4a, b). In addition, severely deformed platelets are observed like lips. The formation of platelets is mainly caused by the extrusion and accumulation of sand particles on the material surface. As the sand particles hit, the accumulated material organization is further squeezed and stretched.

As shown in Fig. 5a, the worn microstructure exhibited highly deformed irregular pits related to primary FCC phase and less deformed regular lamellar micro-cutting corresponding to eutectic microstructure. Under the impact of sand particles, the coarser primary FCC phase deforms easily and large while the FCC/Laves dual-phase constitution bears the same impact with less deform. After multiple extrusions, highly deformed platelets around primary FCC phase formed and rose up to become a lip. Meanwhile, the FCC lamella matrix in eutectic microstructure eroded by small particles during multiple extrusions formed micro-cutting and micro-indent, as shown in Fig. 5b. The surface roughness of worn EHEA in Fig. 5c is related to the worn microstructure in Fig. 5a. The surface roughness of SS and MCS is quite different from that of EHEA, as shown in Fig. 5c, indicating that the micro-indentation caused by sand impaction plays a significant role in the slurry erosion of material surface. The micro-indentation of SS and MCS is deeper because of their low hardness and yield strength.

4 Conclusion

In this study, the slurry erosion properties of NiCoCrFeNb_{0.45} EHEA in sand water flow were studied and compared with MCS 1045 and SS 04Cr13Ni5Mo that are commonly used in hydraulic machinery. The erosion rate of EHEA is

Fig. 4 Scanning electron microscopy images of **a, c** SS 04Cr13Ni5Mo **b, d** NiCoCrFeNb_{0.45} EHEA after slurry erosion testing at 30° impingement angle

Fig. 5 **a** Scanning electron microscopy image and **b** high-magnification scanning electron microscopy image of NiCoCrFeNb_{0.45} EHEA after slurry erosion testing at 30° impingement angle, **c** Roughness for different materials after corrosion

significantly lower than that of MCS 1045 and SS 0Cr13Ni5Mo. NiCoCrFeNb_{0.45} EHEA is composed of an FCC/Laves dual-phase constitution and exhibits good toughness and hardness, which greatly enhances its erosion resistance. The slurry erosion mechanism of NiCoCrFeNb_{0.45} EHEA and SS 04Cr13Ni5Mo showed micro-cutting, plowing and the formation and removal of platelets. Due to the combined lamellar structure of hard Laves phase and soft FCC phase, the erosion mechanism of NiCoCrFeNb_{0.45} EHEA is different from that of the MCS 1045 and SS 0Cr13Ni5Mo.

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