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Materials

Cavitation erosion behavior of WC coatings on CrNiMo stainless steel by laser alloying

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Abstract: The WC powder was precoated on the surface of CrNiMo stainless steel and then made into an alloying layer by using the laser alloying technique. Phases in the layers were investigated by X-ray diffraction (XRD) analysis and surface morphologies after cavitation erosion were observed with the help of scanning electron microscopy (SEM). The cavitation erosion behavior of the CrNiMo stainless steel and WC laser alloying layer in distilled water was tested with the help of ultrasonic vibration cavitation erosion equipment. The results showed that the thickness of the laser alloying layer was about 0.13 mm. The layer had a dense microstructure, metallurgically bonded to the substrate, and no crack had been found. The cavitation erosion mass loss rate of the laser alloying layer was only 2/5 that of the CrNiMo stainless steel. The layer had better cavitation resistance properties because of its metallurgical combination and the strengthening effects of the precipitate phases.

Key words: martensite stainless steel; laser surface alloying; cavitation erosion; WC

1. Introduction

In a fast-flowing (or vibrating) liquid, when local pressure in the liquid drops below a certain level, there will be cavities (or bubbles) nucleating and growing. The cavities collapse when being transported to a high-pressure region in the liquid. Together with the collapse of the cavities, there are shock waves and micro-jets, which exert stress pulses on the liquid-solid interface vicinity. Repeating pressure pulses on the interface cause fatigue failure and eventually material loss, such a damage mode is called cavitation erosion [1].

Cavitation erosion is one type of surface erosion mechanism. Laser surface modification is a suitable technique to improve the cavitation erosion resistance of steels. It could modify the surface properties of the steel but retain the mechanical properties of the steel substrate, by using only small amount of precious materials. Among the different techniques available, laser surface modification has the virtue of being able to form a surface layer with strong, metallurgical bonding to the stainless steel substrate [2-4]. There are already many kinds of laser surface modification methods to enhance the cavitation erosion properties of stainless steels [1, 5]. In this experiment, WC powder was used to improve the cavitation erosion resistance of CrNiMo stainless steel by the laser surface alloying method.

2. Experimental methods

The substrate is CrNiMo stainless steel, whose composition (wt%) is Cr 13.63, Ni 4.01, Mo 0.61, Mn 0.55, C 0.03, P <0.01, S <0.019, Si 0.47, Al <0.005, and Fe balanced. After vacuum deoxidation refine (AOF) melting, the steel was heat treated at 1000°C for 3 h (air cooling), then tempered at 480°C for 2 h. The matrix of CrNiMo stainless steel was tempered martensite and its mechanical properties were: yield strength (σ_b), 1020 MPa; tensile strength ($\sigma_{0.2}$), 880 MPa; elongation (δ), 15%; area reduction (ψ), 58.5%; impact energy (A_{KV}), 101 J; Vickers-hardness (Hv), 380; and yield ratio ($\sigma_{0.2}/\sigma_b$), 0.86. Fig. 1 shows the shape and size of the sample.

Laser surface alloying was performed using JHM-1GY-400 YAG LASER. Table 1 shows the process parameters of the laser alloying experiment.

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Table 1. Process parameters of WC laser alloying experiment

Electric current/A	Scanning velocity/($m \cdot s^{-1}$)	Pulse width / ms	Frequency / Hz
170	5	3.0	45

The samples were cut in the vertical direction of the laser alloying layer, polished and etched with nitric acid solution (5vol% nitric acid+90vol% alcohol). The microstructure of the alloyed layer was analyzed by optical microscopy and scanning electron microscopy (SEM). Phases in the layer were tested by X'Pert Pro MPD-PW3040/60 X-ray diffractometry (XRD), with the Cu K_{α} radiation source. Vickers microhardness of the samples was measured at 0.245 N load, 0.1 mm measure distance, and 10 s loading saturation time.

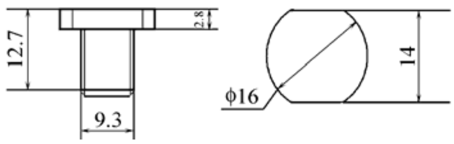

Fig. 1. Shape and size of the sample (unit: mm).

The cavitation erosion test used the XL 2020 supersonic vibratory cavitation erosion facility, with 20 kHz vibration frequency, 550 W power, and 60 μm peak to peak amplitude. The experiment proceeded in distilled water kept at 18°C. The samples were ultrasonically cleaned, dried, and weighed by an electronic balance (accurate to 0.1 mg) every 30 min.

3. Results and discussion

3.1. Metallographic analysis

When the laser irradiated on the surface of the sample, fine WC powder dissolved into the melt pool formed by the melting substrate. Then the melt pool rapidly solidified to form a WC alloyed layer. Laser parameters were determined by observing the macrostructure of a single track alloying layer. When the laser electric current was 180 A, there were ablation phenomena on the laser track. Although it could get a more uninterrupted alloying layer, the surface quality became worse because of the ablation. On the other hand, when the laser electric current was below 160 A, the laser power density (the power level in one unit facula surface) was insufficient to melt the WC powder and the stainless steel substrate, and there was still unmelted WC powder in the alloying layer. Only suitable processing parameters could get uniform alloying layers without a crack. Contrasting their macro- and microstructure, the best parameters were selected as shown in Table 1. Following this the overlapping alloying layer was made using those parameters.

Fig. 2 shows the cross-sectional microstructure of the overlapping alloying sample. The micrograph is composed of the alloying layer and the heat-affected zone (HAZ). The thickness of the alloying layer is about 0.13 mm, and that of the HAZ is about 0.18 mm. The alloying layer makes metallurgical bonding with the substrate and its crystal grain is finer than that of the CrNiMo stainless steel substrate.

Fig. 3 shows the XRD patterns of phases in the CrNiMo stainless steel and the laser-alloyed layer. The CrNiMo stainless steel substrate is mainly composed of FeNi and FeCr solid solution (as shown in Fig. 3(a)). After the laser alloying treatment, fine WC powder dissolves into the melt pool, and then solidifies to form different types of metal carbides and tungsten carbides such as W_2C, Ni_4W, $MoNi_4$, Fe_6W_6C, *et al*. (as shown in Fig. 3(b)).

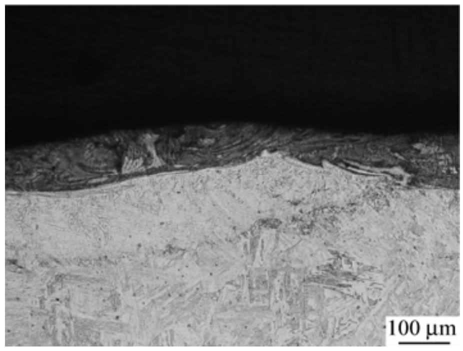

Fig. 2. Optical micrograph of the laser alloying layer.

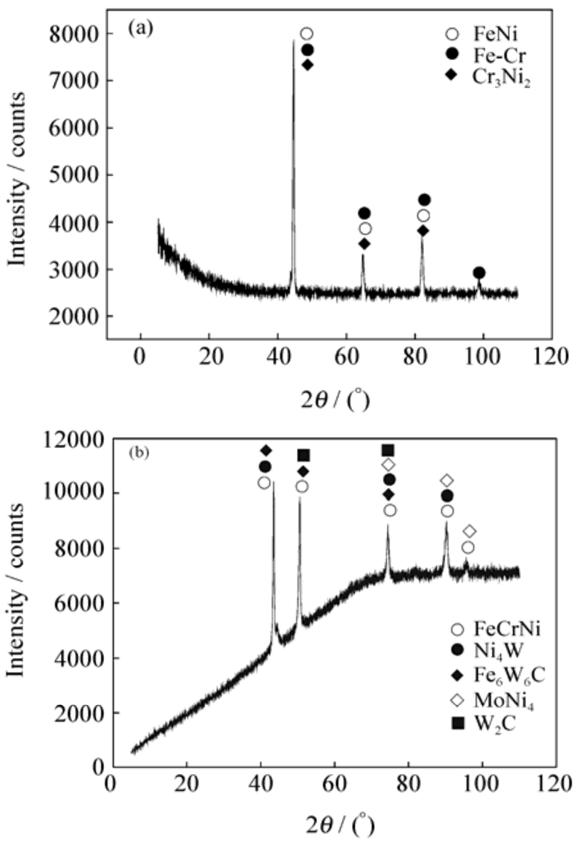

Fig. 3. XRD patterns of the substrate (a) and the laser alloying layer (b).

Fig. 4 shows the microhardness distribution of the laser alloying layer. The microhardness decreases gradually from the alloying layer, heat-affected zone, to CrNiMo substrate. The alloying layer has the highest microhardness value, Hv 487, about 1.3 times that of the CrNiMo stainless steel substrate (Hv 380). The microhardness of the alloying layer significantly increases because of the high cooling rate during laser treatment, precipitate carbides, and solid solubility of C and W in the steel substrate [6].

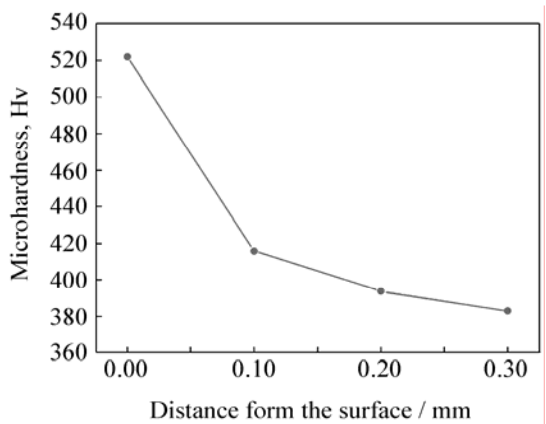

Fig. 4. Microhardness distribution curve along the depth of the laser alloying sample.

3.2. Cavitation erosion resistance

Fig. 5 shows the curves of the cumulative mass loss (Fig. 5(a)) and the mass loss rate (Fig. 5(b)) of the laser alloying layer and the CrNiMo stainless steel in distilled water. After having been cavitation eroded for 6 h, the mass loss of the alloying layer was 27.9 mg, only 52% that of the CrNiMo stainless steel substrate (53.9 mg). The laser alloying layer has no obvious incubation period during the cavitation erosion process. The mass loss rate of the layer is 5.96 mg/h, which is less than that of the stainless steel substrate. The WC alloying layer has better cavitation resistance properties than the CrNiMo stainless steel substrate.

Fig. 6 shows the surface SEM micrographs of the NiCrMo stainless steel and the laser surface alloying samples during the cavitation erosion process. After being cavitation eroded for 10 min, the surface of the CrNiMo steel is eroded slightly and its material loss is limited between martensite laths (Fig. 6(a)). There is still no obvious damage phenomenon on the alloying layer in the SEM morophology (Fig. 6(d)). Three hours later, micro cavitation erosion pits come into being on the surface of the NiCrMo stainless steel (Fig. 6(b)). The laser alloying layer only shows little material desquamation, no microcracks are found, and there are still some polished alloying layer surfaces undamaged (identified with the white circles) (Fig. 6(e)). Six hours later, the cavitation erosion damage of the CrNiMo stainless steel still occurs and shows steady material desquamation (Fig. 6(c)). The alloying layer tends to desquamate in micro blocks on its surface. There is no crack found and it still has a polished surface that is not damaged by the cavitation erosion effect (identified with the white circle) (Fig. 6(f)). The laser alloying layer shows higher cavitation resistance properties than the CrNiMo stainless steel.

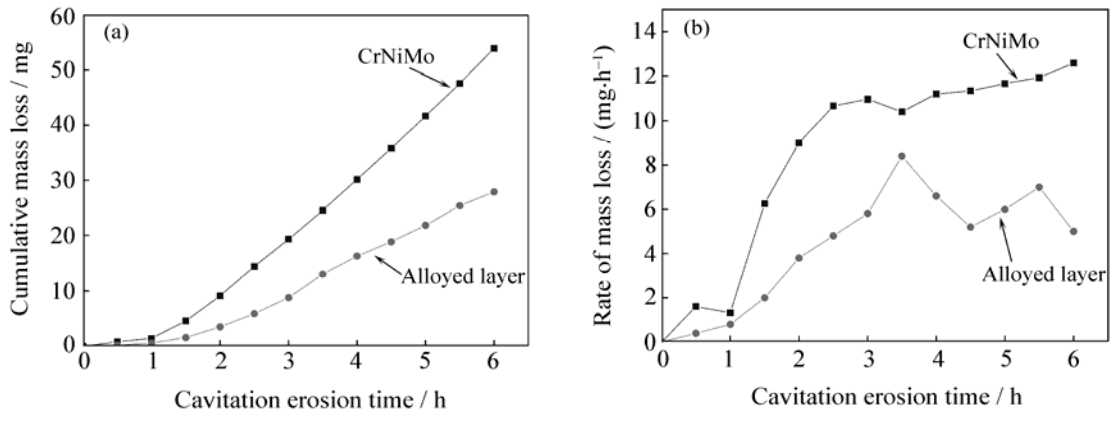

Fig. 5. Cumulative mass loss (a) and mass loss rate (b) curves of the laser alloying layer and the CrNiMo stainless steel in distilled water.

Cavitation erosion was caused by the impact damages when cavities were collapsing close to the surface of the layer. The laser alloying layer got C and W elements from the melting WC powder [7-8]. These C and W elements dissolved into the molten pool and strengthened the layer's matrix [9]. This was the solution strengthening effect of the WC powder. In general, materials that had a homogeneous microstructure and maintained fine reinforce phases, would also have better cavitation resistance properties [10-11]. Precipitated phases such as W_2C, Ni_4W, $MoNi_4$, and Fe_6W_6C also strengthened the layer and improved its fatigue damage resistance properties [12-13].

Large types of hydroturbines need the materials with higher cavitation erosion resistance properties. The CrNiMo stainless steel was used in large hydroturbines. The CrNiMo steel has good mechanical properties, but still needs better surface properties. The laser surface alloying technique could make less expensive WC alloying layers on a stainless steel substrate rapidly. It is still possible to improve the cavitation erosion properties of CrNiMo stainless steel for hydroturbine manufacturing.

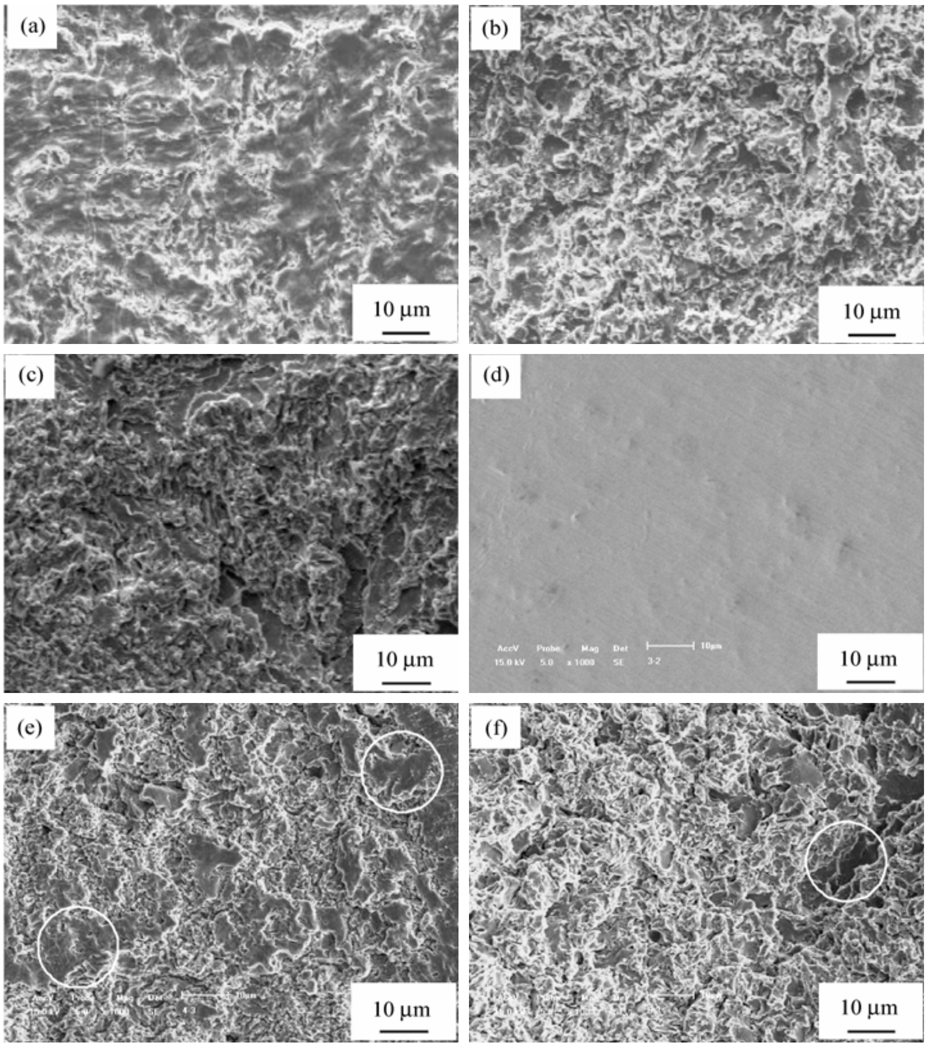

Fig. 6. SEM morphologies of the surface after cavitation erosion: (a) CrNiMo, 10 min; (b) CrNiMo, 3 h; (c) CrNiMo, 6 h; (d) alloying layer, 10 min; (e) alloying layer, 3 h; (f) alloying layer, 6 h.

4. Conclusions

(1) The WC laser alloying layer without cracks was successfully obtained on the CrNiMo stainless steel substrate by a Nd:YAG pulse Laser. The alloying layer had a uniform microstructure and tight metallurgical bonds to the substrate. The thickness of the layer was about 0.13 mm.

(2) The WC alloying layer was strengthened by precipitated phases such as W_2C, Ni_4W, $MoNi_4$, and Fe_6W_6C. The microhardness of the layer was Hv 487 on average, 1.3 times that of the CrNiMo stainless steel substrate (Hv 380).

(3) The cavitation erosion mass loss rate of the WC alloying layer was only 2/5 that of the CrNiMo stainless steel substrate. Furthermore, it had better cavitation erosion damage morphologies than CrNiMo stainless steel.

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