Microstructure, wear and electrochemical behaviors of laser cladding Fe-based coatings with various molybdenum contents

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Abstract

Fe-based alloy coatings with different Mo contents were fabricated on 45 steel substrates by laser cladding. X-ray diffractometer (XRD), scanning electron microscope (SEM) and energy dispersive spectrometer (EDS) were used to analyze the phase composition and microstructural evolution of the coatings. The effects of Mo addition on the wear and electrochemical behaviors of the coatings were analyzed by ball-on-disc wear tester and electrochemical workstation. The results showed that the addition of Mo could help refine grains and promote the transition of dendrites to equiaxed grains. With the increase of Mo content, the hard phases changed from Fe₂B to Mo₂FeB₂. Mo and Cr tended to aggregate in the intercrystalline regions in the form of hard phases. When the Mo content was 4.8 wt%, the hardness increased by 3.6 times compared with that of the substrate. The wear resistance of the coatings increased with the Mo addition. Mo played the role of fine grain strengthening and solid solution strengthening, which was beneficial for the improvement of the hardness and wear resistance. Polarization curves and electrochemical impedance spectroscopy test results revealed that the addition of Mo could improve the corrosion resistance of Fe-based coating.

1. Introduction

Laser cladding is a kind of surface modification technology with the characteristics of small heat-affected zone, controllable dilution rate and good combination with the substrates. It can strengthen the surface of the workpieces and effectively increase their service life [1–3]. Fe-based alloy powder is widely used in laser cladding because of its low price and good compatibility with steel. However, the wear and corrosion resistance of Fe-based alloy cladding layers are limited, which cannot meet the performance requirements of some application fields [4–6]. Therefore, researchers have considered to add alloying elements into Fe-based alloy to improve the properties of the coatings [7–13]. For example, Gao et al [10] studied the effect of Ti content on the microstructure and hardness of laser cladding Fe-based coating. The results showed that adding a certain amount of Ti was beneficial to the refinement and homogenization of the microstructure. This was mainly because Ti can form carbides and borides with C and B elements, which can play the role of dispersion strengthening. However, when the Ti content in the coating reached 4 wt%, the dilution rate of the coating increased and coarse grain precipitates formed in the coating, so the hardness decreased. The effect of Ni on the corrosion behavior of FeSiB₃Ni cladding layer in 3.5% NaCl solution was studied by Zhou et al [11]. They found that with the increase of Ni content, the amorphous content of the coating increased, together with the corrosion potential and the charge transfer resistance of the coating. The addition of Ni can form a NiO passive film on the coating surface, which helped improve the corrosion resistance. They also studied the effect of Al and Ti elements on FeSiB laser cladding coatings [12]. The results showed that Al was beneficial to improve the wear and corrosion resistance of the coating. Ti had little effect on the wear resistance of the coating, but it can reduce the corrosion resistance. Wang et al [13] investigated the effect of rare earth element on laser cladding Fe-based coating and the addition of La₂O₃ was conducive to grain refinement. Due to the fine grain strengthening and
dispersion strengthening effect of the rare earth element, the hardness and wear resistance were improved. The above results suggested that adding proper alloying elements can improve the properties of the laser cladding Fe-based alloy coating.

Molybdenum (Mo) is an important alloying element in steel and cast iron [14, 15]. It has high hardenability and solid solution strengthening effect [16–18]. Meanwhile, Mo can also react with C and B elements to form carbides and borides, which can help improve the plasticity and ductility of the Fe-based materials [19, 20]. For example, You et al [21] studied the effect of Mo content on the microstructure and mechanical properties of Fe–B–C sintered alloy. The addition of Mo promoted the transformation of the microstructure to pearlite (or pearlite/bainite) and the grain boundary also changed with the increase of Mo content. When the Mo content was 5.0 wt%, the grain boundary turned to a lamella structure composed of MoFe (C, B) and (Fe, Mo)3(C, B). After adding Mo, the mechanical properties of the Fe–B–C alloy were significantly improved. Ouyang et al [22] reported the influence of Mo on the high temperature corrosion behavior of as-cast Fe–3.5B alloys. With the increase of Mo content, the matrix phase transformed into Mo-contained solid solution and the eutectic phases changed into Mo-contained borides. A certain amount of Mo addition helped stabilize the reticular structure in the microstructure. By comparing the microstructure evolution of alloys with different Mo contents and the corrosion behaviors in molten zinc, it was found that 8.0 wt% Mo alloy exhibited the best corrosion resistance. Wang et al [23] fabricated Mo-contained Fe-based hard-facing coatings by shield manual arc welding method and studied the effect of Mo on the microstructure and wear resistance of the coatings. Mo that dissolved into the matrix can play the role of solid solution strengthening. Meanwhile, Mo can also participate in the formation of Mo2C carbides. The volume fraction of carbides in the coating increased with the Mo content, together with the hardness and wear resistance. However, cracks appeared in the coating with higher Mo content. It can be seen from the above literatures that the addition of Mo can effectively improve the microstructure and properties of Fe-based materials. At present, there are limited studies on the effect of Mo on laser cladding Fe-based alloy coatings and available research mainly concentrate on the wear resistance of the coating.

45 steel is a widely-used medium carbon structural steel with good mechanical properties and low price. However, the parts made from 45 steel often face serious surface wear when serving in harsh environments, so it is necessary to strengthen the surface of 45 steel. Feng et al [24] used laser cladding technology to repair the damaged 45 steel engine crankshaft, and realized remanufacturing repair by depositing Fe-based coating on its surface. The repaired parts can not only maintain its original shape, but also obtain improved performance. The results showed that the hardness of the coating was 2–3 times higher than that of the 45 steel substrate. Zhu et al [25] systematically studied the laser remanufacturing strategy of 45 steel gear. They used H13 steel powders to repair the damaged 45 steel gear tooth and compared its mechanical properties with the standard 45 steel specimen. It was found that after laser cladding, the remanufactured tooth could basically restore the appearance before breakage, and obtain the properties of a higher hardness and better wear resistance. In this study, Fe-based coatings with different Mo contents were deposited on 45 steel substrates by laser cladding. The influence of Mo addition on the phase composition, microstructural evolution, wear and electrochemical behaviors of the coatings were studied. The corresponding results can provide an experimental basis for further improving the corrosion and wear performances of the laser cladding Fe-based coatings.

2. Experimental procedures

2.1. Preparation of materials and coatings

The substrate material used in the experiment was 45 medium carbon steel and its chemical composition was 0.42 ~ 0.50 wt% C, 0.25 wt% Cr, 0.50 ~ 0.80 wt% Mn, 0.25 wt% Ni, 0.035 wt% P, 0.035 wt% S, 0.17 ~ 0.37 wt% Si and the rest of Fe. Fe901 alloy powders and FeMo70 ferro-molybdenum powders were adopted as the laser cladding material. The change of different Mo contents in the mixed powders was realized by adjusting the ratio of the two raw materials. The chemical composition of the mixed powders was listed in table 1. The mixed powders were placed in a planetary ball mill (QM-3SP04, Nanjing NanDa Instrument Plant) for homogenization. The ball-to-powder weight ratio was 2:1, the milling speeding was 400 r min−1 and the milling time was 6 h, respectively. After ball milling, the powders were placed in a 100 °C drying oven for 2 h to remove residual water. The morphologies of Fe901, FeMo70 and mixed powders (4.8 wt% Mo for example) are shown in figure 1. As can be seen from figure 1(c), the two powders are evenly mixed and the powder sizes are reduced due to ball milling.

The laser cladding experiment was conducted with a semiconductor laser processing system. The experimental device and the schematic diagram were shown in figure 2. High-purity argon was used as the protective gas to avoid the oxidation of the powders during the cladding process. The method of preset powder was used in the experiment and the mixed alloy powders were evenly laid on the surface of the substrate before cladding. The quality of the cladding coating was related to the laser processing parameters. After a series of tests,
the optimal processing parameters were chosen and listed in Table 2. Single-track and multi-track cladding layers were prepared for microstructure analysis and properties tests.

### 2.2. Characterization method

The surface crack condition of the cladding coatings was examined by dye penetration method. The first step was to clean the coating surface with the cleaning agent. The second step was to spray the penetrant evenly on the surface of the coating. After 10 min, clean the penetrant with the cleaning agent and then spray the developer. If there are cracks on the coating surface, they will appear after a few minutes. The macroscopic morphologies of the coatings before and after the dye penetration tests were recorded by camera.

![Figure 1. SEM morphologies of the raw powders: (a) Fe901; (b) FeMo70; (c) mixed powders.](image)

![Figure 2. (a) The experimental device; (b) the schematic diagram of the laser processing system.](image)

| Chemical element | Sample number | Cr | B  | Si  | Mo | C  | Fe  |
|------------------|---------------|----|----|-----|----|----|-----|
| S1               | 13.0          | 1.6| 1.2| 0.8 | 0.15| Bal.|     |
| S2               | 13.0          | 1.6| 1.2| 1.8 | 0.15| Bal.|     |
| S3               | 13.0          | 1.6| 1.2| 2.8 | 0.15| Bal.|     |
| S4               | 13.0          | 1.6| 1.2| 3.8 | 0.15| Bal.|     |
| S5               | 13.0          | 1.6| 1.2| 4.8 | 0.15| Bal.|     |

| Laser power | Scanning speed | Focus length | Spot size | Overlapping rate |
|-------------|----------------|--------------|-----------|-----------------|
| 3 kw        | 6 mm s⁻¹       | 215 mm       | 3 mm × 4 mm | 50%             |
The phase constitution of the coatings was analyzed by an x-ray diffractometer (XRD, D8 ADVANCE, BRUKER). The test parameters were CuKα radiation at 40 kV and 40 mA. The samples were scanned in the range of 10°—100° in a step-scan mode.

The specimens were cut along the cross section of the coatings with a wire cutting machine and made into metallographic samples with a hot mounting machine. The metallographic samples were polished with 240—2000# sandpapers in turn and polished until the surface was bright and free of scratches. Then the samples were corroded by Leford aqua regia (HNO3:HCl = 3:1, in vol%), washed with alcohol and dried. The cross-section morphology and microstructure of the coatings were characterized by an optical microscope (OM, Vert. A1, ZEISS) and a field emission scanning electron microscope (FESEM, SIGMA HD, ZEISS). Meanwhile, the chemical composition of the coatings was analyzed by an energy dispersive spectrometer (EDS, OXFORD) that was attached to the scanning electron microscope.

2.3. Hardness and wear test
An HVS-1000 Vickers microhardness tester was used to test the microhardness from the surface of the cladding coating to the substrate along the depth direction with a load of 200 g and a loading time of 15 s. The test points were selected every 0.1 mm and three different points were tested at the same horizontal position to obtain the average value.

The friction and wear experiments were carried out by a ball-on-disc friction wear instrument (MS-T3001, Lanzhou Huahui Instrument Technology Co., Ltd) with a load of 2000 g and a load time of 60 min. The size of each sample was 22 mm × 15 mm × 6 mm. The grinding ball was ZrO2 with a diameter of 3 mm, the rotational speed was fixed at 400 r min\(^{-1}\) and the wear scar diameter was 3 mm, respectively. The coefficient of friction (COF) changed continuously over time and was recorded in the computer. Each sample was ultrasonically cleaned in ethanol and dried before and after the wear test. The mass change was weighed by an electronic balance with an accuracy of 0.1 mg to calculate the wear loss.

2.4. Electrochemical corrosion experiment
In order to study the effect of different Mo contents on the corrosion resistance of the cladding coatings, the corrosion behaviors of the samples were tested in a 3.5% NaCl solution with an electrochemical workstation (CHI 760E, CH Instruments). Before the experiment, the samples were welded on the copper wires and embedded with epoxy resin. The exposed surface area was set as 1 cm\(^2\). A three-electrode system was adopted, in which a platinum sheet, a saturated calomel electrode and the coating sample were used as the auxiliary electrode, the reference electrode and the working electrode, respectively. The samples were immersed in the 3.5% NaCl solution for 60 min to obtain the steady-state open circuit potential. The test range of the potentiodynamic polarization curve was the open circuit potential plus 0.4 V and minus 0.3 V. The scanning speed was 1.6 mV s\(^{-1}\). Additionally, the electrochemical impedance spectroscopy (EIS) was employed at the open circuit potential with a sinusoidal potential of 5 mV and a frequency range from 100 kHz to 0.01 Hz.

3. Results and discussion

3.1. Analysis of coating surface morphology and microstructure
Figure 3 shows the macro morphologies of the single-track and multi-track cladding coatings before and after flaw detection. It can be seen from figures 3(a), (c) that the surfaces of the single-track cladding layers with different Mo contents are smooth and continuous, and the surfaces of the multi-track cladding layers are relatively flat without obvious bulges. From the surface morphologies after dye penetration tests in figures 3(b), (d), it can be seen that there is no color penetrant on the surfaces of both single and multi-track cladding layers, indicating that there are no defects like cracks and pores. Thus, the coatings with different Mo contents show good quality.

Figure 4(a) shows the XRD patterns of the Fe-based alloy coatings with different Mo contents. It can be seen that all the coatings are mainly composed of α-Fe and Cr7C3. The difference lies in the existence form of the boride phases. When the Mo content is comparatively low (0.8 wt%, 1.8 wt% and 2.8 wt%), the boride exists in the form of Fe2B. As the content of Mo increases, the peak of Mo2FeB2 gradually appears. When the Mo content is 4.8 wt%, the peak intensity of Mo2FeB2 is stronger, while the peak of Fe2B almost disappears. Meanwhile, it can be seen from the amplification patterns in figures 4(b)−(d) that the peaks of the matrix phase α-Fe phase all shift to the direction of small angle with the increase of Mo content. It can be speculated that the lattice of α-Fe has been distorted and element whose atomic size is larger than Fe has dissolved into it.

The microstructure of the laser cladding coating is generally divided into three regions: the top, the middle and the bottom. Figure 5 is the top regions of the coatings with different Mo contents. The microstructure of the coating with 0.8 wt% Mo (figure 5(a)) is composed of two parts. The upper is equiaxed grains, while coarse
dendritic grains grow below. After adding more Mo, the microstructures become dense and refined. The whole top regions of the coatings are composed of uniform equiaxed grains as shown in figures 5(b)–(e).

Figure 6 shows the middle regions of the coatings with different Mo contents. The dendrites in the coating with 0.8 wt% Mo are long and developed. With the increase of Mo content in the coating, the dendrite length in
The microstructure decreases continuously and the dendrites gradually transform to equiaxed grains. Moreover, it can be seen that the microstructure is obviously refined. When the Mo content reaches 4.8 wt%, fine and dense equiaxed grains separate in the microstructure instead of dendrites.

Figure 7 shows the bottom regions of the coatings with different Mo contents. The coatings are all well bonded with the substrates and white bright bands can be identified. A layer of columnar grains grow perpendicular to the bonding areas. The temperature gradient \((G)\) at the junction at the initial stage of solidification is large, while the growth rate \((R)\) is small. Thus, the \(G/R\) value is comparatively large, which favors the formation of the columnar grains. Similar to the above microstructures, the bottom microstructures of the coatings are also refined with the increase of Mo content.

The typical morphology of the coating is selected for EDS map scanning analysis. It can be seen from figure 8(a) that the coating is composed of intracrystalline and intercrystalline structures. Fe and Si mainly separate in the intracrystalline regions, while Mo, Cr and B are enriched in the intercrystalline regions.
According to the phase composition analysis results, it can be speculated that the main phases inside the grains are \( \alpha \)-Fe matrix phases. Carbide and boride phases such as \( \text{Cr}_7\text{C}_3 \), \( \text{Fe}_2\text{B} \) and \( \text{Mo}_2\text{FeB}_2 \) are distributed in the intercrystalline regions between the grains.

In order to further analyze the effect of Mo on the composition of the coatings, the typical microstructures of the coatings with different Mo contents in figures 9 were tested by EDS point scanning analysis. Point A represents the intracrystalline region and point B represents the intercrystalline region. The EDS point scanning results of different points in figure 9 are displayed in table 3. With the increase of Mo content in the coatings, the Mo contents in the intracrystalline regions increase continuously. This proves that more Mo has dissolved in the matrix phases, which is consistent with the previous phase analysis results. Due to the solid solution of Mo into the \( \alpha \)-Fe matrix, the peaks of the matrix phases move to small angle. Meanwhile, the content of Mo in the intercrystalline region is also increasing, indicating that more Mo-contained phases have formed. The phase composition also proves that Mo-contained phases \( \text{Mo}_2\text{FeB}_2 \) appear in the coating with higher Mo contents.

3.2. Microhardness analysis

The microhardness distribution of the coatings with different Mo contents along the depth direction is given in figure 10. The microhardness distribution curves can be divided into four regions: the cladding layer, the interfacial zone (IZ), the heat affected zone (HAZ) and the substrate. The cladding layer has the highest hardness. The hardness of the interfacial zone is lower than that of the cladding layer. This is because the melting of the
substrate has a diluting effect on the cladding layer, so the hardness of this area is reduced. It can be seen that the hardness of the coatings is much higher than that of the substrate. With the increase of Mo content, the microhardness of the coatings tends to increase. The average hardness of the coating with 4.8 wt% Mo (720.2 HV0.2) is the largest, which is about 3.6 times of the substrate (198.5 HV0.2). The main reason for the increasing hardness includes several aspects. On one hand, the microstructures of the coatings containing more Mo have been refined, so Mo plays the role of fine grain strengthening [26, 27]. On the other hand, Mo has dissolved into the α-Fe matrix and plays the role of solid solution strengthening [28, 29]. Moreover, Mo promotes the formation of hard phase Mo2FeB2, which also helps the increase of the hardness.

3.3. Friction and wear property

Figures 11(a) and (b) show the wear curves and wear loss of the coatings with different Mo contents. It can be seen from figure 11(a) that all the wear curves can be divided into two stages: grinding-in and stabilization. The initial cladding coating has rough surface and small contact areas with the grinding ball, so the concave convex body needs to be ground flat. Therefore, during the running in process, the coefficient of friction (COF) will increase rapidly until it reaches the ‘stable state’ [30–33]. The average COF of the coatings with different Mo contents are 0.4546, 0.3832, 0.3391, 0.2824 and 0.2738, respectively. Moreover, it can be seen from figure 11(b) that under the same wear conditions, the wear loss decreases gradually with the addition of Mo. The wear loss of the coating with 4.8 wt% Mo is 44% that of the Fe901 coating with 0.8 wt% Mo. Therefore, the addition of Mo in the Fe-based coatings is beneficial to improve the wear resistance. The coating containing 4.8 wt% Mo exhibits the best wear resistance.

Figure 12 shows the wear depth curves of the coatings with different Mo contents. It can be seen that the depth of the wear tracks becomes shallower with the addition of Mo. The coating with 4.8 wt% Mo has the smallest wear depth of 15.4 μm, which is nearly half that of the coating with 0.8 wt% Mo.
Figure 10. Microhardness distribution of the coatings with different Mo contents.

Figure 11. (a) Wear curves; (b) wear loss of the coatings with different Mo contents.
In order to further clarify the wear mechanism, the surface morphologies of the coatings after wear tests were studied and the corresponding results are shown in figure 13. As shown in figures 13(a)–(b), the worn surface of the coating with 0.8 wt% Mo has parallel grooves and obvious peeling, indicating that both abrasive wear and adhesive wear occurred during the wear test. With the increase of Mo contents in the coatings, the parallel grooves on the wear surfaces become shallower, and the peeling phenomenon is alleviated obviously. The area of the peeling regions on the surface decreases continuously as shown in figures 13(c), (d), (f), (h). Thus, the wear mechanism of the coatings changes to abrasive wear and slight adhesive wear gradually. When the Mo content in the coating reaches 4.8 wt%, it can be seen from figure 13(j) that there are no obvious grooves and peeling on the worn surface, and some wear debris appear instead, indicating that the wear mechanism of the coating is mainly abrasive wear. The addition of Mo makes the coating microstructure more uniform and finer and improves the microhardness of the coating. This makes it more difficult for the grinding ball to press into the surface of the coating, so as to improve its wear resistance. Moreover, it can be seen from the phase composition analysis that Mo can also promote the formation of hard phases Mo2FeB2. During the wear process, hard phases like Mo2FeB2 and Fe2B in the microstructures can effectively improve the coating’s ability to resist grinding. After the Fe-based matrix is ground away, the hard phases show direct contact with the grinding ball. These hard phases can effectively hinder the continuous grinding of the soft matrix by the grinding ball and play a buffering effect.

3.4. Electrochemical corrosion analysis
3.4.1. Polarization curve
The corrosion resistance of the Fe-based coatings with different Mo contents in 3.5% NaCl solution was evaluated by electrochemical corrosion tests. Figure 14 shows that the potentiodynamic polarization curves of the coatings. It is generally believed that the self-corrosion potential ($E_{corr}$) reflects the thermodynamic tendency of the corrosion. The more positive the $E_{corr}$ is, the more difficult corrosion will occur [34, 35]. With the increase of Mo content, the cathodic polarization curves and anodic polarization curves of the coatings move to the upper left, indicating that $E_{corr}$ is higher with lower corrosion tendency. The polarization curve parameters were fitted by Tafel extrapolation method, and the self-corrosion potential ($E_{corr}$), corrosion current density ($i_{corr}$) and polarization resistance ($R_p$) were obtained. The fitting results are shown in table 4. The corrosion current density ($i_{corr}$) is directly related to the corrosion rate. The smaller the current density is, the slower the corrosion rate is. The $i_{corr}$ values show a decreasing tendency with the increasing Mo content. $R_p$, the polarization resistance, which can be defined as follows [36]:

$$R_p = \frac{\beta_a \beta_c}{2.303(\beta_a + \beta_c)} \times \frac{1}{i_{corr}}$$

Where $\beta_a$ is the anode Tafel slope; $\beta_c$ is the cathode Tafel slope; $i_{corr}$ is the corrosion current density. The polarization resistance $R_p$ is reasonable to evaluate the corrosion resistance of the coating [37, 38]. The $R_p$ values of the coatings are 4239, 16573, 18531, 19079 and 27925 Ω cm$^{-2}$, respectively. The above electrochemical test results show that the addition of Mo in the Fe-based coatings is conductive to improve the corrosion resistance. The corrosion performance is the best when the Mo addition amount is 4.8 wt%.

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Figure 13. Surface morphologies of the coatings with different Mo contents after wear tests: (a)–(b) 0.8 wt% Mo; (c)–(d) 1.8 wt% Mo; (e)–(f) 2.8 wt% Mo; (g)–(h) 3.8 wt% Mo; (i)–(j) 4.8 wt% Mo.
3.4.2. Electrochemical impedance spectroscopy

In order to further study the electrochemical corrosion performance of the coatings, Nyquist and Bode plots were measured and the corresponding results are shown in figure 15. It can be seen that the Nyquist curve characteristics of the coatings with different Mo contents are similar with an obvious capacitance arc. The radius of the capacitance arc increases with the Mo content. The capacitance arc is connected with the charge transfer resistance. The larger the capacitance arc is, the larger the charge transfer resistance is, and the more difficult corrosion can happen [39]. Thus, the Nyquist curves reflect the positive effect of adding Mo on the corrosion resistance of the coatings. The Nyquist and Bode plots were fitted basing on the equivalent circuit shown in figure 15(c). The fitting results are consistent with the experimental data. The total impedance can be expressed by the following equation [40]:

![Figure 14. Potentiodynamic polarization curves of the coatings with different Mo contents in 3.5 wt% NaCl solution.](image)

![Figure 15. (a) Nyquist plots; (b)–(c) Bode plots of the coatings with different Mo contents in 3.5% NaCl solution. (The geometric symbol is the actual measurement data and the solid line of the corresponding color represents the fitting data by the equivalent circuit shown inside).](image)
experimental results are concluded as follows: addition on the microstructure, microhardness, wear and corrosion resistance of the coatings were studied. The Fe-based alloy coatings with different Mo contents were fabricated by semiconductor laser.

4. Conclusion

Fe-based alloy coatings with different Mo contents were fabricated by semiconductor laser. The effect of Mo addition on the microstructure, microhardness, wear and corrosion resistance of the coatings were studied. The experimental results are concluded as follows:

1. Single-track and multi-track Mo-contained Fe-based coatings without obvious defects are successfully prepared on 45 steel substrates. When Mo content is comparatively low, the coating is mainly composed of \( \alpha \)-Fe, \( \text{Cr}_7\text{C}_3 \) and \( \text{Fe}_2\text{B} \). With the increasing content of Mo, \( \text{Fe}_2\text{B} \) phases are gradually replaced by \( \text{Mo}_2\text{FeB}_2 \).

2. The addition of Mo can significantly refine the microstructure of the coatings and promote the transformation of dendrites to equiaxed grains. Mo and Cr are mainly enriched in the intercrystalline regions. With the increase of Mo addition in the coatings, the Mo contents in the intercrystalline and intracrystalline regions all increase.

3. The average microhardness of the Fe-based coating containing 4.8 wt% Mo is the largest with the value of 720.2 HV\(_{0.2}\), which is about 3.6 times that of the substrate. The wear loss of the coating with 4.8 wt% Mo is 44% lower than that of the coating with 0.8 wt% Mo, indicating that the wear resistance is significantly improved. The fine grain strengthening and solid solution strengthening effect of Mo play a key role.

4. The coating with 4.8 wt% Mo has the most positive self-corrosion potential, the lowest corrosion current density and the largest polarization resistance and charge transfer resistance, proving the improvement of the corrosion resistance by Mo addition.

Table 4. Electrochemical parameters obtained from figure 14.

| Sample | \( \beta_{a}/V \) | \( \beta_{c}/V \) | \( E_{corr}/V \) | \( i_{corr}/A\cdot\text{cm}^{-2} \) | \( R_{p}/\Omega\cdot\text{cm}^{-2} \) |
|--------|-----------------|-----------------|-----------------|-------------------------------|-------------------------------|
| S1     | -0.528          | 0.080           | -0.543          | \( 9.657 \times 10^{-6} \) | 4239                          |
| S2     | -0.328          | 0.112           | -0.506          | \( 4.456 \times 10^{-6} \) | 16573                         |
| S3     | -0.337          | 0.124           | -0.495          | \( 4.597 \times 10^{-6} \) | 18531                         |
| S4     | -0.324          | 0.095           | -0.489          | \( 3.059 \times 10^{-6} \) | 19079                         |
| S5     | -0.199          | 0.077           | -0.459          | \( 1.953 \times 10^{-6} \) | 27925                         |

\[
Z = R_s + 1 \left\{ Y_{ob}(jw)^{n_b} + 1 \left\{ R_b + 1 \left\{ Y_{at}(jw)^{n_t} + \frac{1}{R_t} \right\}\right\}\right\}
\]

\[
CPE_b = \frac{1}{Y_{ob}(jw)^{n_b}}
\]

\[
CPE_t = \frac{1}{Y_{at}(jw)^{n_t}}
\]

\( R_s \) represents the solution resistance. \( CPE_b \) is the constant phase element, which can be measured by the constant coefficient \( Y_{ob} \) and the diffusion coefficient \( n_b \). It is parallel to \( R_t \) of the charge transfer resistance. \( R_b \) is the resistance of the corrosion product film. \( CPE_b \) is determined by the constant coefficient \( Y_{ob} \) and the diffusion coefficient \( n_b \). The fitting results of the EIS data are shown in table 5. It is generally believed that \( R_t \) is a parameter closely related to the corrosion rate. Materials show lower corrosion rate and better corrosion resistance when \( R_t \) is higher [12, 41]. The charge transfer resistance of the coatings with different Mo contents are 1593, 2132, 2578, 2864 and 3546 \( \Omega \cdot \text{cm}^{-2} \), respectively. Therefore, the coatings with higher Mo content exhibit better corrosion resistance, which is consistent with the potentiodynamic polarization results.

The reason for the improvement of the corrosion resistance is that the microstructures of the coatings become refined, uniform and dense after adding Mo. Meanwhile, the enrichment of Cr and Mo elements in the intercrystalline regions can also help increase the corrosion resistance. Similar results were reported by other researchers [42]. Yang et al [43] found in the study of 316L stainless steel prepared by laser melt deposition that the high densification and fine cellular microstructures, together with Mo and Cr enrichment at the interfaces, were beneficial to improve the corrosion resistance. In addition, some studies believe that the synergistic effect of Mo and Cr can also improve the corrosion resistance. Mo can be enriched in the rust layers and form ion-selective Mo-contained layers, which promotes the protection effect of the Cr-contained rust layers [44, 45].
Table 5. Parameters obtained from equivalent circuit fitting of the coatings.

| Sample | $R_0$ /Ω·cm⁻² | $Y_{ob} \times 10^{-4}$/Ω·s⁻¹·cm⁻² | $n_b$ | $R_b$ /Ω·cm⁻² | $Y_{ao} \times 10^{-4}$/Ω·s⁻¹·cm⁻² | $n_i$ | $R_i$ /Ω·cm⁻² |
|--------|----------------|-----------------------------------|-------|----------------|-----------------------------------|-------|----------------|
| S1     | 6.761 ± 0.649  | 1.341 ± 0.840                    | 0.851 ± 0.041 | 10.291 ± 0.479 | 3.273 ± 0.141                    | 0.819 ± 0.041 | 1729.3 ± 178.5 |
| S2     | 6.462 ± 0.399  | 2.466 ± 1.547                    | 0.864 ± 0.071 | 10.522 ± 0.722 | 1.634 ± 0.831                    | 0.864 ± 0.071 | 2217.7 ± 76.5  |
| S3     | 7.328 ± 1.138  | 1.817 ± 0.048                    | 0.875 ± 0.013 | 9.377 ± 1.330  | 2.458 ± 0.364                    | 0.650 ± 0.284 | 2507.7 ± 81.0  |
| S4     | 7.111 ± 0.629  | 1.990 ± 1.192                    | 0.865 ± 0.034 | 12.193 ± 0.725 | 2.882 ± 0.039                    | 0.841 ± 0.028 | 2821.7 ± 151.5 |
| S5     | 6.880 ± 0.589  | 1.913 ± 0.084                    | 0.859 ± 0.041 | 10.137 ± 0.360 | 2.155 ± 0.093                    | 0.823 ± 0.019 | 3339.0 ± 113.0 |
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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Credit author contribution statement

Qian Li: Investigation, Data Curation, Writing; Qian Wang: Methodology, Investigation, Conceptualization, Writing-Review & Editing; Liang Zhang: Formal analysis, Visualization; Dong Xu Chen: Method, Supervision; Hui Jin: Investigation; Ji Dong Li: Resources, Supervision; Jun Wei Zhang: Methodology, Supervision, Writing-Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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