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Effect of Different Loading Conditions on the Service Life of Mine Steel Wire in Corrosive Medium

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Long-term corrosion test, constant tensile test and corrosion fatigue test of steel wire were carried out in this paper. According to the results of parameters of electrochemical corrosion, equivalent stress distribution of pit bottom, and morphology of steel wire surface and fracture, the coupled action of stress and corrosion on the failure of mine steel wire was discussed. It was found that the corrosion current density of steel wire in the initial phase of corrosion fatigue test was about 20 times higher than that in long-term corrosion test, and the radio increased for the effect of the cyclic load during the test, which also showed that the corrosion rate of steel wire would be greatly increased by the load. In addition, the equivalent stress distribution of pit bottom was related to the load and corrosion degree, and equivalent stress value appears to be associated with this effect which marginally increases with increasing corrosion degree of steel wire under the same load. The corrosion of surface was strengthened with the increase of load, and cyclic stress may result in crack formation. Meanwhile, the brittleness of steel wire increased under the interaction of load and corrosion. Obvious plastic deformation was not observed in corrosion fatigue test, but brittle completely.

Keywords: Steel wire; corrosion rate; stress corrosion cracking; corrosion fatigue; finite element model

1. INTRODUCTION

2.As an important bearing device in coal mine production, the safety and reliability of mine steel wire rope is very important to mine production and miner's life [1]. Wire rope are braided and twisted by steel wire, and the phenomenon of broken wires often appears in extremely harsh conditions [2]. J. Toribio [3-4] analyzed the failure of cold drawn prestressing steel wires subjected to stress corrosion cracking and discussed the fracture profile of the different steel wires in the anodic regime of

cracking. While in situations of pure stress corrosion cracking such a value is even higher than the fracture toughness of the material in air (due to crack tip blunting), in the case of hydrogen embrittlement there is a marked reduction of stress intensity factor value, which indicates that these steel wires are highly susceptible to this phenomenon. Additionally, Hormaza [5] studied the fatigue failure of a slickline wire induced by corrosion pits. This analysis revealed that the operation of the wire produced a series of superficial discontinuities, comprising corrosion pits, fatigue crackings and wear grooves, which provided several stress raisers which served as the initiation point for the failure. All these studies show that the main fracture patterns of steel wires are stress corrosion crack and corrosion fatigue fracture, and both of the fracture patterns are caused by the interaction of stress and corrosion.

Meanwhile, the effect of stress and corrosion on the service life of materials has been widely studied. Parkins et al [6], Manfredi et al [7], Zhu et al [8], Chu et al [9] and Lu et al [10] studied the stress corrosion cracking mechanisms of metals in different solutions, and Ingolfur et al [11], Fleck et al [12], Ye et al [13] and Ishihara et al [14] studied the corrosion fatigue behavior of different metals, respectively. All the results indicated that the failure rate of material will be greatly enhanced by the influence of stress and corrosion [15-17]. Abreu [18] found that stress corrosion cracking is a localized damage process resulting from the combined action of tensile stresses and environmental attack. Meanwhile, Gutman [19] believed that the interaction could greatly reduce the service life of metal materials. In addition, many new methods were developed in the process of studying the coupled action of stress and corrosion on the service life of metal materials [20, 21].

But in this process, the influence of different stress state on the corrosion rate was not analyzed in quantity. In particular, the failure mechanism of material under different stress state was not fully distinguished, and the coupled action of stress and corrosion on the service life of material was not clear. In addition, in the research of the service life of steel wire, the study on the coupled action of stress and corrosion was less. In order to study the coupled action of stress and corrosion on the failure of steel wire, long-term corrosion test, constant tensile test and corrosion fatigue test of steel wires were carried out in this paper. The effect of different stress state on the corrosion state of steel wire was analyzed in quantity, which was based on the results of corrosion current density values and the Nyquist plots, and the influence mechanism of stress and corrosion on the failure of steel wire was proposed by the analysis of the surface morphologies, fracture morphologies and FE models of steel wires. And in this process, the failure mechanism of steel wire under different stress state was compared.

2. EXPERIMENTAL PROCEDURE

Steel wire of 6×19 point-contact wire ropes with 1 mm diameter was selected in this paper. Table 1 and Table 2 [22] show the chemical composition and mechanical properties of steel wire, respectively, and Table 3 [23] shows the specific components of corrosion solution.

Composition	Fe	Mn	Si	Ni	С	S	Р
Percentage	94.62	4.53	0.02	0.01	0.84	0.001	< 0.001

Table 1. Chemical compositions of steel wire (in wt. %)

Table 2. Mechanical properties of steel wire

Mechanical	Tensile	Yield	Young	Elongation	Section
properties	strength	strength	modulus	ratio	shrinkage
Value	1750MPa	1300MPa	210GPa	24.19%	34.78%

Table 3. Typical water quality composition of coal mine

pH -		Ion content / mg/L						
	\mathbf{K}^+	Na^+	Ca ²⁺	Mg^{2+}	Cl	SO_4^{2-}	HCO ₃ ⁻	
6.97	11.73	141.16	80.56	49.33	89.33	551.38	18.92	

Firstly, long-term corrosion test without load (according to GB/T 19746-2005 [24]) was carried out by immersing steel wire in the corrosion solution, and the non-corrosive surface was coated with rosin wax to ensure the worksheet area in solution wire was 1 cm². The corrosion solution was changed every 3 days in 30 days of testing period. Polarization curve of steel wire in long-term corrosion test and electrochemical impedance spectroscopy of steel wire in corrosion fatigue test were measured by electrochemical workstation of IM6ex type. A three-electrode system was used with Pt as the auxiliary electrode, saturated Ag-AgCl as the reference electrode and steel wire specimens as working electrodes. When measuring the polarization curve, the potential scan range had an open circuit potential of electrodes (relative to the Ag-AgCl electrodes) ± 500 mV and a scan rate of 1 mV/s. Electrochemical impedance spectroscopy (EIS) tests were carried out with a frequency of 10^{5} - 10^{2} Hz and an AC signal amplitude of 5 mV. Impedance data obtained from the tests were fitted to obtain kinetic parameters of corrosion using Zsimwin software. The corrosion fatigue test were measured by the electrochemical both in long-term corrosion test and corrosion fatigue test were measured by the electrochemical workstation.

Fig. 1 shows the instruments and principle of constant tensile test (according to GB/T228.1-2010 [25]). The length of steel wire in solution was 3.18 cm to make sure that the worksheet area in solution was 1 cm². The corrosion solution was changed in a consistent manner with the long-term corrosion test. The load of steel wire was obtained by the senor on the left side of test-bed. In order to avoid yield and creep, the stress corrosion behavior of steel wire was studied mainly under the load of 0% UTS (0 MPa, UTS represents the ultimate tensile strength), 50% UTS (875 MPa) and 70% UTS (1225 MPa). The electrochemical impedance spectroscopy was measured by electrochemical workstation of IM6ex type, while the surface and fracture morphologies of steel wire were observed by SEM.



Figure 1. Instruments and principle of constant tensile test

Finally, corrosion fatigue test (according to GB/T 20120.1-2006 [26]) was carried out on fatigue machine of PYW-20 type under the maximum load of 1000 MPa, with loading frequency of 5 and stress radio of 0.5, as shown in Fig. 2. Similarly, the worksheet area of steel wire in solution was 1 cm². The change of corrosion current density of steel wire under the open circuit potential (relative to the Ag-AgCl electrode) was collected by using IM6ex electrochemical workstation, while the surface and fracture morphologies of steel wire were observed by SEM.



Figure 2. Principle map of corrosion fatigue test

3. RESULTS

3.1 Coupled action of stress and corrosion on the electrochemical corrosion behavior of steel wire

Fig. 3 shows the Nyquist curves of steel wires under different load at different test times in constant tensile test. The steel wire broke at load of 1225 MPa after 23-day testing period, while no fracture occurred on the steel wire with load of 875 MPa within 30 days.

Fig. 3a shows the Nyquist curve of steel wire under three different load after testing for 1 hour. The Nyquist curves of steel wires are all formed by a high frequency capacitive arc and a low frequency capacitive arc at three kinds of stress state. The radius of high frequency capacitance arc which represents the characteristics of corrosion product film of steel wire is smaller than the radius of low frequency capacitive arc, with the latter represents the characteristics of layer amid the wire surface and the rust layer. Curve in the high frequency region indicates that the high frequency capacitance arc characteristic of steel wire is the most obvious. Meanwhile, the high frequency capacitance arc characteristic decreases and becomes no longer complete under the action of load. The results showed that the cracking of corrosion product film occurred by the effect of load, while the protective effect of the film on the substrate decreased. Curve in the low frequency region shows that the radius of low frequency capacitance arc increasing with the increase of the load after testing for 1 hour. Though the size of capacitive arc is related to the corrosion resistance of material, the increase of the steel substrate and corrosion product film, which was caused by the damage of the wire surface. And the damage of wire surface will increase with the increase of the load.

The differences of low frequency capacitance arc radius under different load decrease with the extension of test time. There is no significant difference in low frequency capacitance arc radius after testing for 3 days, and the radius of low frequency capacitance arc under the condition without load becomes the largest after testing for 13 days, as shown in Fig.3c and 3b. This result is due to that the corrosion resistance of steel wire is improved by the effective protection of dense corrosion product film on the matrix. While the corrosion resistance of steel wire with load decreases for the cracking formed on the surface of corrosion product film.



Figure 3. Nyquist plots of steel wires under different loads (a) at 1 h, (b) at 1 d, (c) at 3 d, (d) at 13 d

Fig. 4a and Fig. 4b show the polarization curve and corrosion potential of steel wires in longterm corrosion test. Fig. 4c and Fig. 4c show the corrosion current density variation curves of steel wire under the open circuit potential in long-term corrosion test and corrosion fatigue test respectively.

In long-term corrosion test, the corrosion current density is 9 μ A/cm² after soaking for 1 h and gradually increases to about 23 μ A/cm² after soaking for 240 h. The volatility of the corrosion current density before soaking 312 h is bigger than that in the subsequent immersion time. In corrosion fatigue test, the corrosion current density of steel wire under the open circuit potential has a tendency to increase (200-900 μ A/cm²). The pits gradually formed on the surface of steel wire for the effect of corrosion, which produced large amount of plastic deformation zone. At the same time, the wire surface area in the solution increased for the damaging of the surface of steel wire under the cyclic loading, which caused the increase of the corrosion rate of steel wire.



Figure 4. Polarization curve (a) and corrosion potential (b) of steel wires in long-term corrosion test, and corrosion current densities of steel wires (c) in long-term corrosion test and (d) in corrosion fatigue test

The comparative studies of Fig. 3 and Fig. 4 show that the corrosion current density of steel wire in the initial phase of corrosion fatigue test is about 20 times larger than that in long-term corrosion test without load. The surface of steel wire is constantly exposed to fresh substrate for the fatigue load, which caused the increasing of the corrosion current density of steel wire. And at the end of corrosion fatigue test, the corrosion current density of steel wire before fracture is about 90 times larger than that in long-term corrosion test at the same of time. The corrosion current density can reflect the corrosion rate of steel wire. All these results can illustrate the effect of different stress states on the corrosion state of steel wire in quantity, and prove that the corrosion rate of steel wire will greatly increase with the application of load at the same time.

3.2 Coupled action of stress and corrosion on the stress distribution of steel wire near the pit

Some pits were formed on the surface of steel wire for the effect of corrosion, and the size of the pit was related to the corrosion degree. In generally, the size of the pit will increase with the aggravation of the corrosion degree. According to the surface morphology of steel wire in corrosion solution in constant tensile test, hemispherical model for the radius of the pit was established in this paper, meanwhile the radius of the pits were respectively assumed to $10 \ \mu\text{m}$, $50 \ \mu\text{m}$ and $100 \ \mu\text{m}$. The equivalent stress distribution near the pit of steel wire under different stress states and different corrosion degrees was studied by simulating the corrosion degree of steel wire with the radius of the pit.



Figure 5. Three dimensional finite element models of steel wires (a) with the corrosion pit radius of 10 μ m, (b) with the corrosion pit radius of 50 μ m, (c) with the corrosion pit radius of 100 μ m

A three dimensional finite element model of steel wire with corrosion pit was established according to the steel wire parameters, as shown in Fig. 5. Different stress states and corrosion degrees can lead to different sizes of corrosion pits. According to the micrographs of corrosion pits of steel wire in different tests [22, 23], wire diameter was set at 1 mm, and the radius of the corrosion pits were to be set to 10 μ m, 50 μ m, and 100 μ m, respectively. The models of steel wires were divided into 9952, 7830, 8716 8-node three-dimensional entity unit reduction integral unit (C3D8R), respectively. And local refinement near the corrosion pit was carried out to prevent vertical displacement and rotational

displacement of steel wire bottom [27, 28]. It's known that the elastic modulus of steel wire was 210 GPA and Poisson's ratio was 0.3. 875 MPa and 1225 MPa of loads were imposed to the top of steel wire at simulation constant tensile test and sinusoidal pressure was applied to the top of steel wire with maximum load of 1000 MPa, loading frequency of 5 and stress ratio of 0.5 at simulation corrosion fatigue test.

Fig. 6 shows the equivalent stress distribution diagram of steel wire with different corrosion pit radius and load, which is simulated by ABAQUS software. Meanwhile the value of equivalent stress is shown in Fig. 7.

The study indicated that the maximum equivalent stress was reached at the bottom of corrosion pit and extended along the perpendicular direction of load, as shown in Fig. 6. The result can explain that the crack at the direction perpendicular of the load can be found near the corrosion pit under the effect of stress corrosion. The equivalent stress at the bottom of the pits increased with the applied tensile force if the pits were at the same size and also increased with pit radius at the same load. The minimum equivalent stress (910 MPa) was reached when the pit radius was 10 μ m and the load was 875 MPa, while the maximum equivalent stress (1920 MPa) was reached when the pit radius is 100 μ m and the load is 1225 MPa, which had been beyond the tensile strength of steel wire.

The corrosion degrees of steel wires were considered same when the corrosion pits had the same size. The stress concentration phenomenon at the bottom of pit was more obvious with the increase of the load, which caused the increase of equivalent stress. The stress concentration area had a trend of outside expansion along the vertical direction to the load, and the direction was the main crack propagation direction. The results of expansion increased the area of steel wire matrix (as the anode area), which accelerated the corrosion rate for the acceleration of the process of anodic dissolution. While the outside expansion trend of main crack became more obvious with the acceleration of corrosion under the same load. The increase of load can accelerate the corrosion rate of steel wire. Meanwhile the strong anodic dissolution process can accelerate the main crack propagation. The stress corrosion cracking (SCC) susceptibility of steel wire will be improved by the effect of interaction between load and corrosion, which cause the reduction of the service life of steel wire.





Figure 6. Equivalent stress distribution near the pit of different radius under different load

Fig. 8 shows the equivalent stress changes of each point with different distances to the pit (with radius of 100 μ m) bottom of steel wire in one cycle in corrosion fatigue test. The equivalent stress change of each point accorded with the law of sine wave, which was similar to the load of steel wire. The equivalent stress decreased gradually along the inward direction from the bottom of pit.

The contrast between Fig.7 and Fig. 8 showed that the equivalent stress distribution at the bottom of pit with the same radius was influenced by the form of load. The equivalent stress at the bottom of the pit was much larger than the load in constant tensile test. Meanwhile the equivalent stress at the bottom of the pit was much larger than both the load and the stress of the internal region in corrosion fatigue test. The greater the load, the higher the degree of corrosion, and the lager the equivalent stress at the bottom of pit.

The equivalent stress value of the pit bottom increases with the increase of pit radius under the same load. In addition, the result that load can accelerate the corrosion was shown in the 3.1 quarter. The combination of the two results can shown that the stress and corrosion reinforce each other and their synergistic effect will greatly accelerate the failure speed of steel wire.



Different applied stress (MPa)

Figure 7. Equivalent stress of the pit bottom of different radius under different load



Figure 8. Equivalent stress changes of each point near the pit bottom of steel wire in one cycle (S=1000 MPa, f=5 Hz, r=0.5)

3.3 Coupled action of stress and corrosion on the surface morphology of steel wire

Firstly, the surface morphologies of steel wires under different load in constant tensile test were studied. Fig.9 shows the surface morphologies of steel wires under the load of 0 MPa, 875 MPa and 1225 MPa after testing for 2 days, respectively. The direction of damage on the surface of steel wire under the three different conditions is all along the axial direction. The damage degree under load was significantly higher than that under the condition without load. Moreover, the damage would be aggravated by the raise of load.



Figure 9. Surface morphology of steel wire under different load after testing for 2 days (a) 0 MPa, (b) 875 MPa, (c) 1225 Mpa



Figure 10. Surface morphology of steel wire after corrosion fatigue (*S*=1000 MPa, r=0.5, *f*=5 Hz)

Afterwards, the surface morphology of steel wire in corrosion fatigue test was studied, as shown in Fig. 10. Comparing Fig.10 with Fig.9, a lot of corrosion pits with deeper depth could be found on the surface of steel wire, which showed that the corrosion of the steel wire surface could be aggravated by the application of cyclic loading. Moreover, the raise of load can increase the number of corrosion pits and enlarge the depth of corrosion pits. The damage along the axial direction could be also founded on the surface of steel wire, but the degree of the damage was less severely than that in long-term constant tensile test. In addition, the direction of crack near the corrosion pits is along the

perpendicular direction of load, which could prove the theory that the corrosion pits became the source of crack [29]. No obvious transverse cracks were found on the surface of steel wire in Fig. 9, which showed that constant tensile was not easy to cause crack. The fracture mechanism of steel wire under constant stress was mainly the anodic dissolution.

3.4 Coupled action of stress and corrosion on the fracture morphology of steel wire



Figure 11. Fracture morphologies of steel wires (a) tensile in air, (b) in constant tensile test, (c) in corrosion fatigue test

In order to study the coupled action of stress and corrosion on the fracture morphology of steel wire, the differences of fracture morphology were observed followed by tensile test in the air (according to GB/T228.1-2010 [23]), constant tensile test and corrosion fatigue test, as shown in Fig.11. According to Fig. 11a, the tensile fracture morphology in the air is divided into shear lip and

fiber zone, where in the shear lip is very smooth, although the fiber zone appears to be dimple with intensively distributed deep hole. The fracture morphology under the load of 1225 MPa after testing for 23 days in constant tensile test shows the same portion with air tensile test, as shown in Fig. 11b. While a long transition area appears along the axial direction between the shear lip and wire surface with some trace of drawing. The fiber zone has a very complex morphology coexisted with dimple, quasi-cleavage and tear ridge. The fracture mechanism is more complex, which shows fracture mechanism is more complex, showing some SCC sensibility. The fracture morphology in corrosion fatigue test is consisted of the crack source, crack expansion area and instantaneous fracture zone, as shown in Fig. 11c. The instantaneous fracture zone mainly shows the dimple morphology.

4. DISCUSSION

A dense film oxide film will be formed on the surface of steel wire in corrosive medium, which can improve the corrosion resistance steel wire with no applied stress. But the film will be damaged under the applied stresses, which reduce the service life of steel wire. The current density under open circuit potential and EIS can reflect the corrosion rate of steel wire [30, 31]. The results of corrosion current density test (Fig. 4) showed that the application of fatigue load could greatly accelerate the corrosion speed of steel wire, and the results of Nyquist plots of steel wires under different loads (Fig. 3) showed that the applied load, the faster the corrosion rate of steel wire.

Both constant load and cyclic load can accelerate the expansion of corrosion pits, but only the cyclic load can make the extension direction of pits transverse. While based on the analysis of fracture morphology, the transverse crack in the pit is the source of fatigue fracture. As shown in Fig. 9 and Fig. 10, the load state and corrosion solution have a great influence on the surface and fracture morphology of the steel wire. In the same corrosion solution, the corrosion degree of the steel wire surface is not serious under the condition without load. But load can accelerate the corrosion rate of steel wire, and the severity of corrosion and damage on the tissue surface shows a positive association with load. Moreover, alternating stresses may cause a crack near the pit, which is vertical to load. Same to the study of F. Cao [32] and B. Y. Fang [33], the smooth tensile fracture morphology in the air shows that obvious plastic deformation occurs in the test, meanwhile, the dimple morphology of fiber zone shows that the fracture mechanism of steel wire tested in the air is mainly the ductile fracture. The coexistence of dimple, quasi-cleavage and tear ridge in the fracture morphology of steel wire shows that the fracture mechanism of steel wire in the constant tensile test is coexisted with the ductile fracture and the brittle fracture. According to the study of Z. Shi [34] and B. S. Padekar [35], the ductility of the cracking indicated that the stress corrosion cracking mechanism of steel wire in the constant tensile test was probably hydrogen enhanced localized plasticity. And the fracture morphology of smooth crack source and quasi-cleavage crack expansion area shows that the fracture mechanism of steel wire in the corrosion fatigue test is the brittle fracture [23].

In addition, during the study of corrosion fatigue behavior of steel wire, the effect of different stress states (with different stress ratio of 0.05, 0.25 and 0.5, loading frequency of 2 Hz) on the

corrosion fatigue behavior of steel wire were mentioned. Fig.12 showed the equivalent stress changes of the pit bottom in one cycle (obtained by the finite element simulation) and corresponding surface morphology of steel wire. Obviously, there is a very close relationship between the surface morphology and the stress state (stress ratio). The number of transverse corrosion fatigue crack increased with the increase of stress ratio. In addition, the number of fatigue crack was also associated with the test time, and the larger the stress ratio, the longer the service life of steel wire, but the stronger the effect of corrosion.



Figure 12. Equivalent stress changes of the pit bottom in one cycle and corresponding surface morphology of steel wire

4.5. CONCLUSIONS

(1) The corrosion current density of steel wire in the initial phase of corrosion fatigue test is about 20 times larger than that in long-term corrosion test without load, and the corrosion current density before fracture is about 90 times larger than that in long-term corrosion test at the same of time. All these results can illustrate the effect of different stress states on the corrosion state of steel wire in quantity, and prove that the corrosion rate of steel wire will greatly increase with the application of load at the same time.

(2) The radius of low frequency capacitive arc increases with the rising of the load, and the reduction of corrosion resistance of steel wire is caused by the damage of the corrosion product film with the extension of test time. Meanwhile, the maximum radius of low frequency capacitance arc is caused by the more dense corrosion product film under the condition without load.

(3) The equivalent stress at the bottom of corrosion pit is associated with stress state and corrosion degree. The corrosion degree of wire has positive correlation with the equivalent stress at the bottom of corrosion pit, and the load also has positive association with severity of corrosion and damage on the tissue surface. The load and corrosion reinforce each other and the synergy of them can greatly accelerate the failure of steel wire.

(4) The integrated effects of stress and corrosion result in the formation of crack around the corrosion pits in corrosion fatigue test, while the constant tensile is not easy to cause crack. Ductile fracture are commonly seen in air tensile wire, but brittleness may aggravate with the interaction of stress and corrosion in solution, and in case of corrosion fatigue test, complete brittle fracture with no significant plastic deformation is noted.

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