Simulation Analysis of Stress Corrosion of H62 Copper Alloy

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ABSTRACT: H62 copper alloy is a commonly used material in engineering, and stress cracking of copper alloys has always been concerned. In this paper, a two-dimensional model of H62 copper alloy was established by COMSOL electrochemical module, and the stress corrosion of H62 copper alloy was analyzed by using measured engineering stress-strain curve. The results show that the tensile stress has a serious effect on the stress corrosion, and the excessive tensile stress will lead to the fracture failure of the contact.

1. The introduction
Stress corrosion is the metal damage caused by the combined action of stress and environmental corrosion[1-3]. It is the damage mode caused by multiple factors such as vibration. Stress corrosion can be explained by slip dissolution theory and can be summarized into four processes: slip, film rupture, anodic dissolution, and repassivation. The "passivated film theory" or "film rupture theory" indicates that if corrosion failure occurs under the action of stress or active ions[4], it is first manifested as the breakdown of the passivated film. The damaged part becomes the anode. The stress concentration at the crack tip reduces the anode potential and speeds up the anodic dissolution[5]. As shown in Figure 1, the failure of the surface passivation film under stress is due to a slip step formed due to local plastic deformation near the crack tip. According to "anodic dissolution theory", the continuous dissolution of anodic metal leads to the nucleation and propagation of stress corrosion cracks, which leads to the destruction of the alloy structure. The joint action of stress and corrosive medium results in the formation of micro-erosion holes or crack sources on the metal surface. The channel of microcorrosion hole and crack source is very narrow, and the solution inside and outside the hole is not easy to convection and diffusion, forming a closed area, which is similar to the crack corrosion.

The aluminum alloy components of the German Led Zeppelin 70 years ago developed stress corrosion[6-8]. Similar stress-corrosion ruptures occurred soon after in the Apollo lunar module and giant Saturn rockets[9]. Gruhl[10] pointed out that in aqueous solution, the cathode reaction produces H+, which diffuses through the grain boundary in the alloy and accumulates in the high stress field, thus promoting the occurrence of internal cracks. Puiggali[10] studied the mechanism of stress corrosion cracking of AlZn3Mg alloy in NaCl solution. Scanmans[11] believes that SCC arises from mechanochemical corrosion at the surface, but the propagation is dominated by hydrogen embrittlement. Stress corrosion is widely used in all kinds of mechanical structures, and H62 copper alloy is one of the most widely used alloys. Therefore, it is representative to carry out stress corrosion simulation of H62 copper alloy.
2. The theoretical analysis
Stress corrosion is the metal damage caused by the combined action of stress and environmental corrosion. Generally, only tensile stress can cause stress corrosion cracking (SCC), while compressive stress can prevent or delay the occurrence of stress corrosion cracking. Therefore, in order to simplify the calculation, a two-dimensional H62 copper alloy model was established, as shown in FIG. 2. On the rectangular model with a length of 200mm and a width of 1.91mm, there was a semi-elliptical coating failure area of A =10mm and B =1.15mm, and the model was covered with electrolyte. Simulating the influence of tensile stress on the corrosion of H62 copper alloy.

Copper alloy in the material library is defined as reed material property, and the engineering stress and strain of copper is introduced into the elastoplastic material model of copper in the form of interpolation function, as shown in Figure 3, and the other material parameters are shown in Table 1. The anode reaction occurred in the failure area of the coating. The polarization curve of H62 copper alloy under the solution with a temperature of 35°C and a mass fraction of NaCl of 5% was taken as the anode boundary condition in the form of interpolation function. The cathode reaction occurred on the whole reed surface.
FIG3. Engineering stress - strain curve of copper

Table.1 The mechanics properties of contact basis material

| Density /kg·m$^{-3}$ | Young's modulus /GPa | Poisson's ratio /MPa | Tensile strength /MPa | Compressive strength /MPa | Tensile limit /MPa |
|----------------------|-----------------------|----------------------|-----------------------|--------------------------|-------------------|
| 8960                 | 103.2                 | 0.33                 | 350                   | 200                      | 550               |

Since the reed needs to be stretched, a minimal initial displacement is given to the reed in the X-axis direction. A fixed constraint is added to the left end face of the reed, and the deformation of the lower end face is fixed in the y-direction. A displacement is specified on the left end face of the reed, and the displacement is parametric scanned. After the parameter variables and boundary conditions are defined, the stress corrosion model is meshed, and the meshing type is free triangular mesh. In order to improve the calculation accuracy, the maximum mesh size of the end face on the reed is set to 0.0002m, and the mesh size of the rest can be ultra-refined. The finished mesh division is shown in figure 4. Steady state can be selected for different tensile stresses.

Elastoplastic simulation of the corresponding forces on copper was carried out, and isotropic strengthening model was selected. The strengthening function $\sigma_{y\text{hard}}$ could be expressed as:

$$
\sigma_{y\text{hard}} = \sigma_{\text{exp}}(\varepsilon_{\text{eff}}) - \sigma_{\text{yc}} = \sigma_{\text{exp}}(\varepsilon_{\text{p}} + \frac{\sigma_{\varepsilon}}{E}) - \sigma_{\text{yc}}
$$

Where $\sigma_{\text{exp}}$ is Experimental stress function derived from measured engineering stress - strain curve of copper, $\varepsilon_{\text{eff}}$ is total effective strain, $\sigma_{\text{yc}}$ is yield strength of copper, $\varepsilon_{\text{p}}$ is Plastic strain, $\sigma_{\varepsilon}$ is the effective strain, and $E$ is Young's modulus. Von Mises yield criterion is used in the elastoplastic simulation. Various strains are applied longitudinally on the reed. The tensile strain applied is the total strain, whose magnitude is equal to the total strain deformation divided by the spring length, and the local strain may vary due to the presence of defects.
The influence of elastic and plastic deformation on the anode reaction equilibrium potential can be expressed as:

\[ \Delta \phi_{a,eq}^\prime = \frac{\Delta P V_m}{z F} \]

\[ \Delta \phi_{a,eq}^p = -\frac{TR}{z F} \ln \left( \frac{\alpha v z F N}{N_0} \right) \]  

(2)

Where \( \Delta \phi_{a,eq}^\prime \) is the equilibrium potential change of the anodic reaction caused by elastic deformation, \( \Delta \phi_{a,eq}^p \) is the equilibrium potential change of the anodic reaction caused by plastic deformation, \( \Delta P \) is one third of the uniaxial tensile stress. \( V_m \) is the molar volume of copper, and \( V_m = 7.13 \times 10^{-6} \text{m}^3 \). \( z \) is the copper ion charge number, and \( z = 2 \). \( T \) is the thermodynamic temperature of the environment, \( T = 308.15 \text{K} \). \( v \) is a direction dependent factor, and \( v = 0.45 \). \( \alpha \) is the coefficient of factor, and \( \alpha = 1.67 \times 10^{11} \text{cm}^{-2} \). \( N_0 \) is the initial dislocation density before plastic deformation, and \( N_0 = 1 \times 10^8 \text{cm}^{-2} \).

Continuous elastoplastic tension \( \phi_{a,eq} \) expression as:

\[ \phi_{a,eq} = \phi_{a,eq}^0 - \frac{\Delta P V_m}{z F} \frac{TR}{z F} \ln \left( \frac{\alpha v z F N}{N_0} \epsilon_p + 1 \right) \]  

(3)

Where \( \Delta P \) is excess pressure of elastic deformation limit, the magnitude is equal to one third of the yield strength of copper.

Mechanical deformation results in the redistribution of electrochemical inhomogeneity and the increase of the area of the cathode reaction. In addition, the increase of slip steps, microcracks and surface defects during plastic deformation reduces the activation energy of hydrogen evolution. Xu\(^{[12]} \) considered the increase of exchange current density during plastic deformation, and obtained a semi-empirical expression to describe the influence of mechanical electrochemistry on the cathode reaction through a large number of finite element simulation and experimental data correction and verification:

\[ i_e = i_{0,c} \times 10^{\sigma_{Mises} \cdot b_c} \]  

Where \( \sigma_{Mises} \) is Von Mises stress, \( b_c \) is Cathode Tafel slope. The plastic deformation of structural mechanics will affect the equilibrium potential of anode reaction, which in turn will affect the electrode potential, and the stress will affect the exchange current density of cathode, so that the structural mechanics field and electrochemical physical field can be coupled.

3. Analysis of simulation results

As shown in figure 5, the elastic limit of von Mises stress in the damaged area of the coating is 350MPa. When the given displacement is 3.75\( \times \)10\(^{-4} \)m and 4\( \times \)10\(^{-4} \)m, the von Mises stress of the reed has an area exceeding 350MPa and plastic deformation occurs, while the rest areas and the rest displacements can only have elastic deformation. Only plastic deformation affects the equilibrium potential of the anode. When the displacement is 3.75\( \times \)10\(^{-4} \)m, the area of plastic deformation is about 0.0046m to 0.0138m. When the displacement increases to 4\( \times \)10\(^{-4} \)m, the area of plastic deformation is about 0.0040m to 0.0166m. With the increase of displacement, the area of plastic deformation increases, and the range of stress corrosion also increases.
FIG.5 Changes of von Mises stress in the damaged area of the coating

The corrosion current distribution in the damaged area of the coating is shown in figure 6 and figure 7. The corrosion current distribution of the anode and cathode is similar to the von Mises stress distribution. When the coating is under tensile stress, the current density in the edge area of the coating suddenly increases, and then the current density gradually increases until it reaches its maximum value at the center of the coating failure area. The increase of tensile stress can accelerate the stress corrosion. In addition, the wedge action of volume expansion of corrosion products can also promote stress corrosion.

FIG.6 The anodic local current density distribution in the damaged area of the coating

FIG.7 The cathode local current density distribution in the damaged area of the coating

The two-dimensional von Mises stress distribution of the reed model is shown in figure 8 and figure 9. When the displacement is $4 \times 10^{-4}$m, the maximum von Mises stress is $4.65 \times 10^8$N/m$^2$. The stress corrosion increases gradually from the outer side to the center of the coating damage area, and the deeper the coating damage area, the more serious the stress corrosion, too much tensile stress will lead to the contact fracture failure, and the macro direction of crack and tensile stress vertical. In order to prevent stress corrosion, electrical connectors can be protected by improving the corrosive environment. At present, the most common measure is to spray adsorptive film corrosion inhibitor on the electrical connector, which can effectively isolate the electrical connector from the liquid film and delay the occurrence of corrosion.
4. Conclusion
The tensile stress causes the H62 copper alloy to crack gradually at the failure point, and the crack gradually expands with time. The greater the tensile stress, the more obvious the cracking is. Stress corrosion can be intensified when the metal is coupled with an anode current.

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