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Study on corrosion resistance of copper matrix composites reinforced by Al2O3 whiskers

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Abstract

The corrosion behavior of copper matrix composites with different Al2O3 whisker content in NaCl solution (3.6 wt%) at different temperatures was studied by electrochemical test and electron microscope. The results showed that with the increase of Al2O3 whisker content, the corrosion tendency of the composites first increases and then decreases. The charge-transfer resistance (Rct) value and corrosion current density tend to decrease first and then rise slowly. The whiskers can cause huge differences in performance in different directions so that it is easy to agglomerate and entangle in the matrix, which can increase the heterogeneity of materials in copper matrix alloys, hence, the addition of whiskers will cause the increase of corrosion phenomenon. As the whisker content continues to increase, a large number of reinforcing phases will form a natural protective layer when exposed on the metal surface, which will slow down the corrosion situation. As the temperature increases, the corrosion resistance decreases first and then increases. When the temperature increases from 25 °C to 50 °C, the electrochemical reaction is accelerated, the free electrons between the metal atoms obtain external energy, the ion migration rate is accelerated, and the corrosion reaction is more likely to occur. When the temperature increases from 50 °C to 75 °C, the corrosion reaction rate is mainly controlled by the diffusion of oxygen. As the temperature increases, the solubility of oxygen decreases and the cathode reaction requires oxygen to participate, consequently, the corrosion rate decreases. For the microstructure of the corrosion specimen, corrosion mainly occurred at or around the reinforcement phase/matrix interface. Intermetallic compound particles often appear near corrosion initiation points along the reinforcement phase/matrix interface, and the corrosion behavior of composites is mainly determined by copper. Copper is used as the anode of the battery, and the corrosion products are mainly copper chloride salts.

1. Introduction

Copper matrix composites possess lightweight, high stiffness, high fatigue strength, wear resistance, and excellent performance at high temperatures. They are ideal materials for aerospace, power, automotive and military applications, besides, they are widely used in heat sinks and electronic contacts and engine casing, etc [1–3]. However, the composite material exhibits lower corrosion resistance than the monolithic alloy due to the cathode nature of the intermetallic compound particles preferentially formed at the C/substrate interface [4]. Carbon reinforcement acts as an inert electrode on which oxidation of O2 and H+ reduction occurs, which causes preferential erosion so that corrosion resistance may be lower than that of its overall matrix alloy [4, 5]. Hihara et al [6] pointed out that the specific reasons for reducing corrosion resistance are as follows: (1) Electrical coupling between the reinforcing phase and the matrix alloy; (2) Forming an interfacial phase between the reinforcing phase and the matrix; (3) Introduction of alternation of microstructure as well as pollutants during
the preparation process. Rohatgi et al [7] used agitating mixing technology to add graphite particles and titanium to the alloy and studied the corrosion resistance, results had shown that an electrical field existed between graphite and Cu, causing corrosion, in which copper acted as a battery anode dissolved. Moreover, the corrosion rate of C–Cu composites increased with the increase of C content [8]. In addition, by observing the corrosion morphology, it was found that most of the corrosion occurred at the C/Cu interface [9]. The microstructure modification produced by the combination of graphite particles synthesized by electrodeposition technology and copper matrix composites could improve the corrosion resistance of the composite [10]. Mordike et al [11] also proposed carbon fiber as the conductive second phase, and the electrical coupling with carbon fiber aggravated the corrosion behavior of metal matrix composites [12].

Therefore, the choice of the reinforcements requires consideration of the coupling effect between the reinforcement and the matrix alloy. Bakkar et al [13] pointed out that the electrical insulating properties of Al2O3 were different from those of graphite, which had no galvanic effect on pure copper. The corrosion rate of Al2O3/Cu composite in NaCl aqueous solution is comparable to that of pure copper. Sun et al [8] studied the corrosion behavior of Al2O3 dispersion strengthened copper alloy in NaCl solution. The results showed that the corrosion process was controlled by the formation and dissolution of the surface film, and the surface of Al2O3 would affect the coverage of the corrosion products. The presence of the Al2O3 reinforcement may have various effects on the corrosion resistance. The metal matrix composites exhibit a non-uniform solidification system during the preparation process, which can promote the segregation of alloying elements and formation of interfacial precipitates. The potential difference between the new phase and the substrate is an important factor causing corrosion [14].

Among them, alumina whisker is a two-dimensional material with a single crystal structure, which has excellent properties. Therefore, adding it to the composite material can have a good reinforcement effect. However, current researches on Al2O3 reinforced copper matrix composite materials tend to focus on mechanical properties, friction and wear, rather than corrosion resistance. In the previous work of our research group, Al2O3 whisker-reinforced copper matrix composites had been prepared and their mechanical properties had been studied [15]. At that time, Al2O3 particles and whiskers were selected. The purpose is that the existence of the particles can improve the stress transfer between the matrix and the whiskers. At the same time, it can also reduce the direct contact between the whiskers to promote the whiskers dispersing, avoid clusters from causing stress concentration, and improve the mechanical properties of the composite. The purpose of this paper is to explore effect of alumina whiskers on the material’s corrosion resistance in a chlorine-containing medium solution and at three temperatures by using polarization curves, open circuit potentials, and impedance spectroscopy.

2. Materials and methods

In previous work, Al2O3 whisker-reinforced copper matrix composites were prepared, in which the Al2O3 whisker contents were 0, 0.5 wt%, 1 wt%, and 1.5 wt%, respectively [15]. The specimens are numbered as #1, #2, #3, and #4 in order of the whisker content of Al2O3 increasing (table 1). The addition of alumina particles can improve the stress transmission between the matrix and the reinforcing fibers, and reduce direct contact between the fibers to avoid clusters and stress concentration. In order to help lubricate components, solid solution strengthen and refine grains, metal elements such as Ni and Fe are also added. The purpose is to strengthen the alloying elements and refine the grains. At the same time, some alloying elements can play the role of lubricating components.

After the specimen was cut, polished and welded, the back side of the working surface and the copper wire were welded together with Al. The rest of the work surface was sealed with AB epoxy resin and placed in an electric oven (101-OSB) to fully cure. The specimen was degreased, then placed in an ultrasonic cleaner (PS-40) for ultrasonic cleaning, and finally placed in an electric oven to dry. The specimen was polished with a 25% H2O2(50%) + 7 ml H2SO4(98%) + H2O polishing solution. Finally, the specimen was installed in the electrolytic cell as a working electrode. The corrosion test of Al2O3 reinforced copper matrix composites was

| Number | C | Al2O3 whisker | Al2O3 particles | Ni | Fe | Sn | Pb | ZrO2 | La | Cu |
|--------|---|--------------|----------------|----|----|----|----|------|----|----|
| #1     | 7 | 0.0          | 3.0            | 5  | 5  | 6  | 4  | 1.9  | 0.1| 68 |
| #2     | 7 | 0.5          | 2.5            | 5  | 5  | 6  | 4  | 1.9  | 0.1| 68 |
| #3     | 7 | 1.0          | 2.0            | 5  | 5  | 6  | 4  | 1.9  | 0.1| 68 |
| #4     | 7 | 1.5          | 1.5            | 5  | 5  | 6  | 4  | 1.9  | 0.1| 68 |

Table 1. The components of Al2O3 reinforced copper matrix composites [15].
carried out in a chlorine-containing medium solution (3.6 wt% NaCl) at three temperatures (25 °C, 50 °C, 75 °C) through a CS series electrochemical workstation (CS310 in COM3). The open circuit recorded the analysis data through the test program CorrTest, and the frequency was set to 5 Hz. The potentiodynamic scan was performed by using a three-electrode system (figure 1), the saturated calomel electrode was the reference electrode, the platinum plate electrode was the auxiliary electrode, the copper matrix composite was the working electrode, and the potentiodynamic scan was set to ±0.1 V of the open circuit potential. The scan rate was 0.5 mV s⁻¹. Impedance testing was performed by applying a small sinusoidal AC signal to the system under test over a wide range of frequencies to obtain impedance versus frequency. The composite was subjected to phase analysis by x-ray diffraction (XRD). The surface morphology of the specimen was analyzed by scanning electron microscopy (SEM). The crystal structure of Al₂O₃ whiskers and the interface between them and the copper matrix were analyzed by transmission electron microscopy.

3. Results and discussion

3.1. Microstructure of Al₂O₃ reinforced copper matrix composite

Figures 2(a)–(d) presents SEM micrographs of copper matrix composites with varying contents of alumina whiskers. As can be seen from the figure, the entire structure is composed of three different phases, including a white phase dispersed uniformly, a black phase distributed in a stripe, and most of the gray phase. The white phase is Al₂O₃, and the size of the alumina particles becomes smaller in specimens #3 and #4. It can be seen from figures 2(c) and (d) that the average size is 10 μm and it is evenly dispersed in the matrix. The gray phase is a copper matrix. The black phase is graphite, and its distribution is relatively uniform in figures 2(a) and (b), there is no agglomeration, and it is tightly bound to the matrix. With the increase of alumina whiskers, graphite aggregated greatly, the copper matrix was split, and the bond with the copper matrix was not tight enough [15]. The cracks will spontaneously initiate and continue to grow at the interface of graphite and copper matrix. However, in terms of corrosion resistance, graphite can play a physical shielding role between the metal substrate and the corrosive medium, thereby reducing the rate of corrosion of the metal substrate and protecting the metal.

Figure 3(a) is an XRD pattern of the sintered Al₂O₃ reinforced copper matrix composite. It can be seen from the figure that only the Cu peak is detected, and the peaks of Ni, Fe, C, Sn, and Pb are not found. The most intuitive phenomenon is that the XRD pattern of the sintered specimen shows a copper (311) peak, and the corresponding 2θ is 89.245° [15]. Figures 3(b)–(c) shows the TEM results of an Al₂O₃ reinforced copper matrix composite of 0.5 wt% whisker. Figure 3(b) is the microstructure at point 1 and the corresponding energy spectrum result. The upper right corner of figure 3(b) is the electron diffraction pattern at point 1. Combined with the energy spectrum results, it can be concluded that the electron diffraction spectrum in figure 3(b) is an alloy phase formed of elements such as Sn, Fe, and Cu. Figure 3(c) shows the microstructure and corresponding energy spectrum results in other regions of the composite. From the energy spectrum, point 2 is Al₂O₃ particles. Further observations reveal that the Al₂O₃ particles are approximately a few hundred nanometers in size and are well embedded in the copper matrix. However, Al₂O₃ whiskers are not observed due to too little content.

Figure 3(d) shows the bright field image at point 3 and the corresponding spectral results, and the upper right corner is the selected area electron diffraction pattern at point 3. It can be seen from the results of the energy spectrum that the point 3 is graphite. And there is a lot of graphite in the composite and there are some wrinkles on the surface [15].

Figure 1. Three-electrode system.
3.2. Open circuit potential of Al₂O₃ reinforced copper matrix composites

Figures 4(a)–(c) is the open-circuit potential curves of specimens #1, #2, #3, and #4 at 25 °C, 50 °C, and 75 °C, respectively. It can be seen from figure 4(a) that the corrosion potential moves forward and the corrosion...
tendency decreases. Abhijeet et al [16] proposed that when the reinforcement was more inert than the matrix material, the open circuit potential would move to a positive value. At the same temperature, the increase in Al2O3 whisker content in figures 4(b) and (c) increases the corrosion tendency first and then decreases. Among them, the increase in corrosion tendency is due to the fact that whiskers can cause huge differences in performance in different directions, and are easy to agglomerate and entangle in the matrix, which can increase the heterogeneity of materials in copper matrix alloys. Therefore, the addition of whiskers will increase the corrosion phenomenon. Bragaglia et al [17] pointed out that the presence of alumina reinforcements may have various effects on the corrosion resistance of copper-based composites. This strengthening slows down the formation of the passivation film and weakens its protective effect. The presence of Al2O3 particles prevents the formation of a continuous oxide film layer on the entire surface. In addition, alumina whisker-reinforced copper-based composites can be regarded as non-uniform solidification systems during the preparation process, and inert phase enhancement can promote the segregation of alloying elements and the formation of interfacial precipitated phases [18]. From the results of the energy spectrum of figure 3(b), the alloy phase formed can be seen. The formation of the alloy phase may cause the formation of gaps on the one hand, and itself may be a corrosion sensitive point on the other. In addition, the presence of inert Al2O3 whiskers increases the ratio of the perimeter to the area of the substrate, and the presence of whiskers may damage the continuous oxide layer on the surface. However, when the whisker content increases to 1.5 wt%, the self-corrosion potential reaches a maximum value of 0.253 V, and the corrosion tendency decreases, as shown in figure 4(c). Because as the content of whiskers increases, whiskers, graphite, etc will begin to gather outside, and a protective layer will be formed to block the contact between copper and the corrosion solution, and the corrosion tendency will decrease. It can also be seen in figure 2 that graphite appears in large amounts on the surface of the copper matrix composite material. It can be seen from figures 4(a)-(c) that as the temperature rises, the corrosion tendency becomes larger. When the temperature rises, the electrochemical reaction is accelerated, and the free electrons between the metal atoms obtain external energy, making it more prone to corrosion reaction [19].

### 3.3. Impedance spectrum of Al2O3 reinforced copper matrix composites

Figures 5(a)–(c) are impedance spectra of specimens at 25 °C, 50 °C, and 75 °C under 3.6 wt% NaCl conditions. According to the impedance spectrum, there is only one capacitive reactance arc. The equivalent circuit diagram shown in figure 6 is drawn. Table 2 is the electrochemical parameters obtained by fitting the EIS data according to the equivalent circuit. The equivalent circuit shown in figure 6 is used to fit the data. The peak in the high frequency region in figure 5 is related to the presence of Al2O3 and possible passivation film (Rs), and the peak in the low frequency region is related to the charge transfer resistance and capacitance (C1) Related [20]. According to the results, the Rct value of specimen #1 is the largest at 25 °C, which is 219.04 Ω cm². At the same temperature, with the increase of Al2O3 whisker content, the Rct value roughly accords with the trend of
decreasing first and then increasing slowly, indicating that the corrosion resistance of the specimen first weakens and then rises. The reason is that in the 3.6 wt% NaCl electrolytic medium, an oxide film will be formed on the surface of the copper matrix composite to protect the material. However, the specific adsorption of different ions on the oxide film and the possible formation of different products cause the dissolution of the outer porous oxide film and the increase of surface heterogeneity. In addition, a certain number of gaps are formed between the alumina whisker and the surface of the copper-based composite material, and these gaps will serve as the

![Figure 5. Electrochemical impedance of Al₂O₃ reinforced copper matrix composites at different temperatures: (a) 25 °C, (b) 50 °C, (c) 75 °C.](image)

![Figure 6. Equivalent circuit diagram. Rs: solution resistance; Rct: charge transfer resistance; C1: capacitance between the working electrode and the electrolyte.](image)

| Temperature(°C) | Number | Rs(Ω·cm⁻²) | Rct(Ω·cm⁻²) | C1(F·cm⁻²) |
|-----------------|--------|------------|-------------|------------|
| 25              | #1     | 2.2782     | 219.04      | 0.0011109  |
|                 | #2     | 2.3156     | 163.02      | 0.0003823  |
|                 | #3     | 5.6358     | 109.14      | 0.092739   |
|                 | #4     | 6.1803     | 60.087      | 0.036389   |
| 50              | #1     | 1.9626     | 8.0534      | 0.00069546 |
|                 | #2     | 1.7727     | 65.827      | 0.00056739 |
|                 | #3     | 4.9207     | 58.776      | 0.02087    |
|                 | #4     | 4.5054     | 33.657      | 0.042504   |
| 75              | #1     | 1.0118     | 96.98       | 0.005212   |
|                 | #2     | 1.3351     | 46.327      | 0.010119   |
|                 | #3     | 3.1525     | 23.214      | 0.0064827  |
|                 | #4     | 0.60279    | 63.388      | 0.018197   |
starting point for corrosion. Zhang et al. [21] analyzed the electrochemical impedance spectra of copper alloy specimens at 30 °C and 3.5 wt% NaCl solution at different times, and pointed out that the typical semicircle shape of the Nyquist diagram increases with the increase of exposure time. The oxide film resistance also increases, and the peak in the high frequency region is due to the formation of a multilayer protective corrosion product film. When the peak is crossed, the Rct value decreases. Because Al₂O₃ destroys the continuity of the corrosion product film and reduces the corrosion resistance [22]. However, as the whisker content continues to increase, the corrosion resistance increases slowly. Because when there are many alumina whiskers, it will affect the agglomeration effect of the enhanced phase, although it will affect the mechanical properties, but a large number of enhanced phases exposing it to a metal surface will form a natural protective layer, which will alleviate a small amount of corrosion. The impedance spectrum in figure 5 is a typical semi-circular shape, indicating that as the temperature increases, the transfer resistance and the oxide film resistance increase. From figures 5(a)–(c), as the temperature increases, the Rct value decreases. This is because when the temperature increases, the resistance of the chloride medium reduces and the corrosion reaction is accelerated, resulting in a reduction in the corrosion resistance [23]. In addition, the temperature increase will drive the anode reaction at a higher rate, and accelerate the dissolution and corrosion of metal materials.

3.4. Polarization curve of Al₂O₃ reinforced copper matrix composites

Figures 7(a)–(c) are polarization curves of specimens #1, #2, #3, and #4 under conditions of 3.6 wt% NaCl at 25 °C, 50 °C, and 75 °C, respectively. It can be seen from figure 7 that the specimens are all in the active area, and a protective oxide film is formed on the surface of the specimen. Table 3 lists the electrochemical parameters of specimens #1, #2, #3, and #4 at 25 °C, 50 °C, and 75 °C. In terms of corrosion kinetics, the lower the corrosion current, the better the corrosion resistance. It can be seen from the data in table 3 that at the same temperature, as the content of Al₂O₃ whiskers increases, the corrosion current density generally increases first and then decreases. And it is able to see through the polarization curve in figure 7 that with the further increase of the potential, the anode curve does not show a clear peak, which indicates that the formed copper chloride salt film is unstable [24, 25]. This shows that the protective film generated during the corrosion process has been destroyed, so the current density has not decreased. It is universally known that defects in materials are the weak points of the material, which will become the starting point of corrosion. Composites mainly suffer from pitting corrosion at the interface of the reinforcing phase/matrix. Therefore, the accelerated corrosion is caused by the cracks between Al₂O₃ whiskers and the copper matrix. Due to the presence of Al₂O₃ whiskers, the corrosion product protective film is destroyed, and the chemical composition in the composite increases. The discontinuity of the formed the chlorocopper salt film and the difficulty of reformation in which the anode
reaction rate is controlled by the formation and dissolution of the chlorocopper salt film [26]. It can also be seen from figure 2 that the open circuit potential moves negatively, thereby making the composite material more susceptible to pitting. In addition, Al2O3 whiskers will increase the self-corrosion potential of copper matrix composite materials, making the materials vulnerable to pitting attack. Bragaglia et al [17] studied the effect of Al2O3 strengthening and precipitation on the corrosion behavior of metal matrix composites, and pointed out that the comparison with data of unreinforced alloys confirmed that the presence of alumina has a small improvement in corrosion resistance [27]. Although pitting begins with the reinforcement phase/matrix, as the content of alumina whiskers increases, alumina, graphite, etc. are exposed outside the matrix, which will limit the electrical connection between the intermetallic compound particles and the solution, and thus the reaction speed can be slow down. From figures 7(a)–(c), as the temperature increases, the corrosion current density increases first and then decreases, the corrosion rate first increases and then decreases, and the corrosion resistance decreases and then increases. When the temperature increases from 25 °C to 50 °C, the electrochemical reaction is accelerated, the free electrons between the metal atoms obtain external energy, the ion migration rate is accelerated, and the corrosion reaction is more likely to occur. When the temperature increases from 50 °C to 75 °C, the corrosion reaction rate is mainly controlled by the diffusion of oxygen. As the temperature increases, the solubility of oxygen decreases, and the cathode reaction requires oxygen to participate, so the corrosion rate decreases [15].

### 3.5. Corrosion morphology analysis of Al2O3 reinforced copper matrix composites

Figure 8 is the results which can show the corrosion topography of Al2O3 reinforced copper matrix composites #1, #2, #3, and #4 at 25 °C with the energy spectrum results of the corresponding points. It can be clearly seen from figure 8(c) and (d) that Al2O3 whisker-reinforced copper matrix composites have pitting corrosion between the two phases. Pitting corrosion is to weaken and destroy the surface passivation layer by Cl− and so on. When the film is ruptured and chloride ions penetrate into it, the size continues to expand over time, which largely destroys the protective passivation film on the surface of the specimen, and exposes the bare metal to the corrosive environment. For general materials, the weak areas on the surface of the material are prone to produce pitting, such as pores and impurities. For metal matrix composites, the reinforcement material may be treated as an impurity phase due to the small amount of incorporation, and pitting corrosion occurs near the reinforcing phase particles. Al2O3 forms a localized corrosion channel in the metal matrix composite to form deep pits. In the overall matrix alloy, localized corrosion spreads unconstrained in the radial direction to form shallower circular holes. From figures 8(b)–(d), corrosion mainly occurs around the enhanced phase/matrix interface, and intermetallic compound particles are also often found near the corrosion initiation point along the enhanced phase/substrate interface. Zhu et al [4] pointed out that the local corrosion of composite materials is always at the physical or chemical heterogeneity such as reinforcement/substrate interface, defects, intermetallic compounds, mechanical damage zones, grain boundaries, inclusions or dislocations, etc [28]. Since the resistivity of Al2O3 is greater than 1014 Ω·cm, there is no galvanic effect between the Al2O3 reinforcing phase and the matrix [17]. Al2O3 whiskers are more sensitive to corrosion than Al2O3 particles because whiskers and particles can increase material non-uniformity in copper matrix alloys. Hamdy et al [29] pointed out that the corrosion rate of Al2O3 whisker reinforcement is higher and the maximum pit depth is larger than that of the whole alloy. Because the presence of inert Al2O3 whiskers increases the ratio of the perimeter to the area of the matrix, and the presence of whiskers may damage the corrosion product film on the surface [30]. The electrochemical corrosion of Al2O3 reinforced copper matrix composites in solution is shown in formula (1–3). In chlorine-containing media, corrosion is carried out to form copper chloride salts [31]. The elemental
composition of the corrosion starting points 1, 2, 3 was measured. According to EDS, the corrosion product was a copper chloride salt. Since the chloride has water absorption, the copper matrix surface forms a liquid film layer, and the Cl$^-$ radius is small, and the adsorption and penetration force are strong, which can damage the oxide film and cause a large amount of local corrosion. In order to bind to Cu$^{2+}$, Cl$^-$ competes with OH$^-$ to form an unstable chlorinated complex to destroy the formed corrosion product film $[32, 33]$. As the corrosion progresses, Cl$^-$ will enter the pitting partial enrichment, which is equivalent to increasing the contact area of corrosion and accelerating the generation of corrosion. The higher the temperature of the solution, the more severe the corrosion will have different effects on the dissolution of the copper anode $[32, 34]$. The corrosion of Al$_2$O$_3$ on the surface affects the coverage of the corrosion product film. However, the corrosion process is controlled by the formation and dissolution of the surface film, so Al$_2$O$_3$ plays an important role in the corrosion process $[8, 23]$.

Anode reaction: $\text{Cu} - 2e \rightarrow \text{Cu}^{2+}$ \hspace{1cm} (1)
Cathode reaction: $\text{O}_2 + 2\text{H}_2\text{O} + 4e \rightarrow 4\text{OH}^-$ \hspace{1cm} (2)
$\text{Cu} + \text{Cl}^- \rightarrow \text{CuCl} + e^-$ \hspace{1cm} (3)

4. Conclusion

Corrosion behavior of copper matrix composites with different Al$_2$O$_3$ whisker content in 3.6 wt% NaCl solution at different temperatures was studied by electrochemical test and electron microscope. The results are as follows:

1. At the same temperature, with the increase of Al$_2$O$_3$ whisker content, the corrosion tendency of the composite material first increases and then decreases; the Rct value decreases first and then increases; the corrosion current density and rate decrease first and then increase. Because whiskers can cause huge differences in performance in different directions, and are easy to agglomerate and entangle in the matrix, which can increase the heterogeneity of materials in copper matrix alloys. Therefore, the addition of Al$_2$O$_3$ whiskers will increase the corrosion phenomenon. However, as the Al$_2$O$_3$ whisker content continues to increase, the corrosion resistance increases slowly. Because when there are many alumina whiskers, the
agglomeration effect of the enhanced phase will be affected. Although it will affect the mechanical properties, but a large number of enhanced phases exposing it to a metal surface will instead form a natural protective layer, which will slow down the corrosion.

2. In the same whisker content, as the temperature increases, the corrosion current density increases first and then decreases, the corrosion rate first increases and then decreases, and the corrosion resistance decreases and then increases. When the temperature increases from 25 °C to 50 °C, the electrochemical reaction is accelerated, the free electrons between the metal atoms obtain external energy, the ion migration rate is accelerated, and the corrosion reaction is more likely to occur. When the temperature increases from 50 °C to 75 °C, the corrosion reaction rate is mainly controlled by the diffusion of oxygen. As the temperature increases, the solubility of oxygen decreases, and the cathode reaction requires oxygen to participate, so the corrosion rate decreases.

3. For the microstructure of the corrosion specimen, corrosion mainly occurred at or around the reinforcement phase/matrix interface. Intermetallic compound particles often appear near corrosion initiation points along the reinforcement phase/matrix interface, and the corrosion behavior of composites is mainly determined by copper. Copper is used as the anode of the battery, and the corrosion products are mainly copper chloride salts.

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