Abstract: Aluminum alloy components of high-speed trains have a great risk of being corroded by various corrosive medium due to extremely complex atmospheric environments. This will bring out huge losses and reduce the safety and stability of trains. In order to solve the problem, cold spray process was used for repairing the damage of the aluminum alloy components with Al-based powders. Microstructure, mechanical properties and corrosion behavior were studied. The results indicated that there were very few pores and cracks in the repaired areas after repairing. The average microhardness of the repaired areas was 54.5 HV ± 3.4 HV, and the tensile strength of the repaired samples was 160.4 MPa. After neutral salt spray tests for 1000 h, the rate of mass loss of the samples repaired by cold spray was lower than that of 6A01 aluminum alloy. The electrochemical test results showed that the repaired areas had a higher open circuit potential than 6A01 aluminum alloy. As a result, the repaired areas such as the anode protected its nearby substrate. The samples repaired by cold spray exhibited better corrosion than 6A01 aluminum alloy. Cold spray process and Al-based powders are applicable for repairing the aluminum alloy components of high-speed trains.

Keywords: cold spray; aluminum alloy; high-speed trains; corrosion; mechanical properties

1. Introduction

The high-speed railway in China has had rapid developments during these years. Meanwhile, there has been a rapid change in high-speed trains. In order to realize the goal of light weight and a higher speed, aluminum alloy materials are used as car body of high-speed trains, such as 6XXX aluminum alloy and 7XXX aluminum alloy. High-speed trains are running in extremely complex atmospheric environments which include industrial atmosphere, marine atmosphere and rural atmosphere [1,2]. Hence, the components of the car body may be corroded by various corrosive medium. For instance, many corrosion products were observed on the surface of the gutter at the bottom of the train door in the overhaul of trains. The reason is that rainwater, cleaning agents and disinfectants flow on the surface of the gutter, and in this case the gutters often comprise humid and corrosive environments. In addition, general corrosion and the pitting corrosion occur in the floor under dustbins, and galvanic corrosion occurs in the position where aluminum alloys are connected with stainless steel bolts. Therefore, these corrosion problems will cause damage in the aluminum alloy components of high-speed trains. As time passes, the damages will decrease the service life of trains and induce painful financial loss. What is even more serious is the reduction in safety and stability while the train is in motion.

Many technologies can be used for repairing the damage of the components. For instance, metal-inert gas welding (MIG), thermal spray and laser cladding have been
reported [3–5]. However, these processes are limited in the repair of aluminum alloy components of high-speed trains for some reasons. There are many electrical installations around the components; thus, these areas catch fire easily. Hence, although the components repaired by MIG process can meet requirements for utilization, the MIG process is not applicable due to its visible arc. Thermal spray process has no visible arc, but the high temperature acting on the components can easily cause thermal deformation that will increase the difficulty and workload in subsequent processing. Owing to the limit of robot accessibility, it is difficult to repair components in a narrow space with the laser cladding process. Therefore, cold spray process is put forward to solve the problem. Cold spray process has many advantages, such as a low operating temperature, no visible arc and the good accessibility. Assadi et al. [6] and Li et al. [7] provided an overview of cold spray from a material perspective and discussed its applications and developments in detail. They regarded cold spray as a feasible process in solid-state forming of coatings and repairing. The U.S. Army Research Laboratory has used cold spray to repair Al and Mg alloy aircraft components [8,9]. Generally speaking, a high-pressure cold spray system is larger and has a bigger gun in order to guarantee high gas pressure and high velocities of the particles. Thus, the high-pressure cold spray system is heavy and hard to move [10]. By contrast, a portable low-pressure cold spray system is more appropriate for field repairs. Lee et al. [11] used pure Al powders to repair a damaged aluminum mold. The results showed that subsequent machining was needed because there was a little deviation in the dimensional accuracy in the repaired mold. However, this problem may be solved by precise control of the repairing process. Zhang et al. [12] successfully prepared a protective coating on AZ91 alloy by using the cold spray process. The number and size of the pores in the coating with 1 wt.% carbon nanotube were significantly lower compared with pure Al coating. Moreover, the mechanical properties and corrosion resistance also improved. Thus, using cold spray with Al-based powders is a potential method for repairing aluminum alloy components, especially for the aluminum alloy components of high-speed trains.

However, there are few research studies on the detailed microstructure, mechanical properties and corrosion resistance of the repaired parts by cold spray process. In this paper, aluminum alloy sheets with artificial defects were repaired by cold spray with Al-based powders. Microstructure, mechanical properties and corrosion behavior were studied. A comparative study on the samples repaired by superior metal was also conducted. Consequently, the main objective of this research study is to verify the feasibility of the cold spray process in the repair of the aluminum alloy components of high-speed trains.

2. Materials and Methods

2.1. Materials

Extruded 6A01-T5, which is a common material for car body of high-speed trains, was selected as the experimental material. The chemical compositions and the mechanical properties of 6A01-T5 are shown in Tables 1 and 2.

Table 1. Chemical compositions of 6A01.

| Elements | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  | Al   |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Compositions | 0.45 | 0.20 | 0.08 | 0.15 | 0.50 | 0.06 | 0.05 | 0.08 | Bal. |

Table 2. Mechanical properties of 6A01.

| Mechanical Properties/Unit | Thickness/mm | Yield Strength/MPa | Tensile Strength/MPa |
|---------------------------|--------------|--------------------|----------------------|
| Value                     | 4            | ≥205               | ≥245                 |

The raw materials for cold spray consisted of two powders: pure Al powders (74 wt.%) and Al$_2$O$_3$ powders (26 wt.%). The SEM morphologies of the powders are shown in Figure 1. As shown, pure Al powders (D$_{50}$ 23.73 µm) are spherical, and the particle size...
is within the range of 5–40 μm. Al₂O₃ powders (D50 43.94 μm) in the shape of irregular polygons are within the range of 20–60 μm. Due to its low density and high interparticle friction, pure Al powders have a poor flowability. The addition of the irregular Al₂O₃ powders can accelerate the flowability of the powders [13,14]. Hence, the powder feeder will not be blocked, and a supply can be guaranteed.

![SEMmorphologiesoftherawmaterials](image1.jpg)

**Figure 1.** SEM morphologies of the raw materials.

### 2.2. Experiment

In order to simulate the defects caused by corrosion, a pit as depicted in Figure 2 was processed in the center of each aluminum alloy sheet with a thickness of 4 mm. The areas under repair were cleaned by an angle grinder to remove the oxidation film. Then, superior metal and cold spray technology were used to repair the pit.

![Schematic diagram of samples](image2.jpg)

**Figure 2.** Schematic diagram of samples.

Superior metal (LOCTITE 3478) is a two-part ferro-silicon filled epoxy resin system. Resin and hardener were blended together as requested, and the mixtures were used for filling the pits. After 24 h, the repaired areas experienced complete solidification. Before the cold spray process, the powders were kept in a resistance furnace at 60 °C for 3 h in order to make sure that there was no water or moisture in them. The cold spray process was conducted on a low-pressure cold spray system (RF-LP001, Tyontech Co. Ltd, Xi’ an, China). The process parameters were as follows: process gas, air; pressure, 0.65 MPa; preheating temperature, 300 °C; powder feed rate, 25 g/min; gas flow rate, 0.35 L/min. The raised areas were removed in order to obtain a perfectly flat surface after all the aluminum sheets were repaired by the two methods. The samples repaired by these methods are shown in Figure 3.

The repaired sheets were cut into small pieces for different tests. The samples for microstructure analysis were sanded down, polished, etched with a liquid mixture (95 mL H₂O, 2.5 mL HNO₃, 1.5 mL HCl and 1.0 mL HF) and then investigated by an optical microscope (OM, OLYMPUS, Tokyo, Japan) and a field emission scanning electron microscope (SEM, SUPRA55, ZEISS, Jena, Germany). The repaired areas were also observed by SEM and analyzed by an image analysis software (Image J, V 1.6, National Institutes of Health, Bethesda, MD, USA) in order to obtain porosity. The tensile tests as shown in Figure 4 were conducted on a universal tester (WDW-300E, Jinan New Gold Test Instrument Co. Ltd., Jinan, China)
according to EN ISO 6892-1: 2016. The thickness of the samples was 4 mm, and three samples as a group were used for obtaining the average tensile strength. According to the ASTM C633 standard, the bonding strength of the samples was estimated. According to EN ISO 9015-2: 2013, the microhardness of the samples was measured on a microhardness tester (FM-300, FUTURE TECH, Tokyo, Japan) with a test load of 4.9 N for 15 s.

Neutral salt spray tests were carried out in accordance with ISO 11130-2017 in a salt spray test chamber. The samples had a size of 60 mm × 40 mm × 4 mm. Before testing, the surfaces of the samples were polished with 1000# sandpaper and cleaned with ethyl alcohol. The initial mass of the samples was measured by an analytical balance with an accuracy of 0.1 mg. Then, the samples were placed in the test chamber and leant against the bracket at an angle of 20° from the vertical. The test solution was a mixture of deionized water and sodium chloride (NaCl), and the concentration of sodium chloride was 50 g/L. Neutral salt spray tests were conducted at the temperature of 35 °C for 1000 h. After testing, the samples were immersed in a liquid mixture (35 mL H₃PO₄ + 20 g Cr₂O₃ + 1000 mL deionized water) at 100 °C for 10 min in order to remove the corrosion products. The rate of mass loss was calculated by the formula as follows:

\[
R = (W_b - W_a)/S, \tag{1}
\]

\(R\) — the rate of mass loss;
\(W_b\) — the mass of samples before testing;
\(W_a\) — the mass of samples after testing;
\(S\) — the superficial area for testing.

The electrochemical tests performed on the samples were conducted on an electrochemical workstation (CHI 700E, Chinstruments Co. Ltd., Shanghai, China) according to ISO 17475-2005. Three electrodes consist of working electrode (the samples), reference electrode (saturated calomel electrode) and auxiliary electrode (platinum sheet). The open circuit potentials \(E_{OCP}\) of samples before and after neutral salt spray tests were tested in 3.5% NaCl solution. Potentiodynamic polarization tests were conducted with a scanning rate of 0.33 mV/s from −0.5 V to 1.5 V versus OCP.
3. Results and Discussion

3.1. Microstructure

Figures 5 and 6 show the cross-section of samples repaired by superior metal and cold spray. For convenience, the samples repaired by superior metal and cold spray are marked as RSM and RCS, respectively. As shown in Figure 5a, the pit was filled with superior metal. There is a clear interface between the repaired areas and the substrate, and the bonding line is relatively smooth. However, some gaps are obvious in the interface. This demonstrates that the bonding strength will not be too high. Moreover, some pores with different sizes in the repaired areas (RSM) are observed easily. The microstructure of RSM is composed of white ferro-silicon and dark epoxy resin as demonstrated in Figure 6a. As observed in Figure 5b, there are very few pores and cracks in the repaired areas (RCS). As shown in Figure 6b, a mount of irregular particles A exists in the repaired areas. According to the EDS results, the irregular particles A include Al₂O₃ and Al in the other zones B in the repaired areas. The initial morphology of pure Al powders cannot be observed due to plastic deformation caused by the high-speed impact during the repair process. Likewise, some Al₂O₃ particles are broken by this effect. What is more is that it is observed from Figure 5b that some Al₂O₃ particles are embedded in the substrate, so the bonding line is unsmooth and seemingly irregular. It is clear that RCS has a fine mechanical bond with the substrate.

Figure 5. Cross section of samples repaired by (a) superior metal and (b) cold spray.

An image processing software (Image J) was used for calculating the porosity of samples repaired by superior metal and cold spray. Table 3 shows the porosity results of the surface and the cross-section of the repaired areas. The porosity of the surface of these samples is a litter higher than that of the cross-section. Obviously, the RSM samples have a higher porosity than the RCS samples. During the course of repair by superior metals, it was difficult to guarantee that there was no incoming air in the repaired areas. Furthermore, it was hard for air to escape. This can be proved by Figure 5a in which a lot of pores are observed. As a result, the porosity of the RSM sample is relatively high. During the course of repairing by cold spray, the addition of Al₂O₃ particles will promote the plastic deformation of pure Al powders; hence, the porosity between the powder particles was decreased [15].
3.2. Mechanical Properties

3.2.1. Microhardness

Figure 7 is the microhardness of the cross section of samples repaired by cold spray. Microhardness was measured along the line as marked in Figure 7. As observed from the results, the average microhardness of 6A01-T5 is 93.8 HV ± 2.7 HV. The average microhardness of the RCS is 54.5 HV ± 3.4 HV. The microhardness of the RCS samples depends on its microstructure. As mentioned above, amount of Al2O3 particles with relatively high hardness was embedded in the repaired areas. Furthermore, the in situ impact of Al2O3 particles during the repair process will result in work hardening in the repaired areas. Thus, the addition of Al2O3 particles not only decreased porosity but also enhanced microhardness compared with the samples repaired with only pure Al powders [16–18]. According to ISO868, the shore hardness of superior metal is 90D, which is considerably high relative to the substrate. This will not necessarily be beneficial to the entire performance.

3.2.2. Bonding Strength and Tensile Strength

The bonding strength with the substrate of the cold sprayed samples is 35.6 Mpa and that of the superior metal is 31.7 Mpa. This also illustrates that the RSM samples have a lower bonding strength with the substrate. Table 4 shows the adhesion strength and tensile strength and the elongation of samples repaired by superior metal and cold spray. As indicated, the average tensile strength of the RSM samples and the RCS samples is 138.2 MPa and 160.4 MPa, respectively, and the average elongation of them is 1.2% and 2.8%, respectively. According to EN ISO15614-2, the tensile strength of 6A01-T5 weld joints by fusion welding should be more than 147 MPa. It is obvious that the RCS samples have met the requirements, whereas the RSM samples have not.

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**Table 3.** Porosity of the RSM samples and the RCS samples.

| Materials | Surface Porosity | Cross-section Porosity |
|-----------|------------------|------------------------|
| RSM       | 9.246            | 7.597                  |
| RCS       | 3.017            | 2.424                  |

**Figure 6.** Microstructure of samples repaired by (a) superior metal and (b–d) cold spray.
respectively. will be indicated, there were the fusion position of the RCS samples occurred in the repaired areas after tensile tests. Although the substrate is ductile fracture. [19,20]. 

According to the fracture morphologies of the RCS samples, as shown in Figure 9. It can be observed that there are many dimples in the substrate (6A01 aluminum alloy). This demonstrates that the fracture mechanism of substrate is ductile fracture. [19,20]. By contrast, many particles are observed evidently in the RCS, and this can be attributed to its formation mechanism. The raw powders deformed intensely due to the severe impact such that the RCSs were formed by the deposition of the powders in the form of a mechanical bond. Therefore, the fracture positions were mostly in the boundary between the powders. Moreover, it is also proved by the fracture appearance with numerous irregular Al₂O₃ particles. As observed in Figure 9b, there exist some tiny dimples. In conclusion, the fracture mechanism of the RCS consists mainly of brittle fracture and partly of ductile fracture and that of the substrate is ductile fracture.

Figure 7. Microhardness of the cross section of the RCS samples.

Table 4. Tensile strength of samples repaired by superior metal and cold spray.

| Materials | Tensile Strength/MPa | Elongation/% |
|-----------|----------------------|--------------|
| 6A01      | 284.6                | 6.8          |
| RSM       | 138.2                | 1.2          |
| RCS       | 160.4                | 2.8          |

Figure 8 is the macro morphologies of the fracture of samples after tensile tests. As depicted in the Figure 8a, the RSMs were preserved in its entirety and peeled off along the bonding line. In other words, the RSMs have a low bonding strength with the substrate, resulting in the fracture that firstly occurred in the bonding interface. Clearly, the fracture position of the RCS samples occurred in the repaired areas after tensile tests. Although there is only a mechanical bond between the RCS and the substrate, the repaired areas will not fall off from the substrate under the action of stress. SEM was used for analyzing the fracture morphologies of the RCS samples, as shown in Figure 9. It can be observed that there are many dimples in the substrate (6A01 aluminum alloy). This demonstrates that the fracture mechanism of substrate is ductile fracture. [19,20]. By contrast, many particles are observed evidently in the RCS, and this can be attributed to its formation mechanism. The raw powders deformed intensely due to the severe impact such that the RCSs were formed by the deposition of the powders in the form of a mechanical bond. Therefore, the fracture positions were mostly in the boundary between the powders. Moreover, it is also proved by the fracture appearance with numerous irregular Al₂O₃ particles. As observed in Figure 9b, there exist some tiny dimples. In conclusion, the fracture mechanism of the RCS consists mainly of brittle fracture and partly of ductile fracture and that of the substrate is ductile fracture.
Figure 8. Macro morphologies of the fracture of (a) the RSM samples and (b) the RCS samples after tensile tests.

Figure 9. Fracture morphologies of the RCS samples. (a) The interface and (b) the repaired areas.

3.3. Corrosion Behavior

3.3.1. Neutral Salt Spray Tests

Neutral salt spray tests were conducted to study the corrosion behavior of samples repaired by superior metal and cold spray. Figure 10 is the rate of mass loss after neutral salt spray tests. As observed, the rate of mass loss of 6A01-T5 is lower than that of the RSM samples not only after neutral salt spray tests for 500 h but also for 1000 h. By contrast, the RCS samples have the lowest rate of mass loss. That is to say that the RCS samples exhibited better corrosion resistance.

Figure 10. The rate of mass loss of samples after neutral salt spray tests.
The surface appearances of samples before and after neutral salt spray tests are shown in Figure 11. After neutral salt spray tests for 500 h, the 6A01-T5 surface lost its original metallic luster and was covered with grey corrosion products or oxidation film. By comparison, the 6a01-T5 surface for 1000 h is a little darker. The RCS samples exhibited similar surface appearance. After neutral salt spray tests for 500 h, the substrate part is dim, and there exist a small number of corrosive pits in the RCS. Moreover, black trace from the center to the edge of samples is quite clear. This is probably because the corrosion products of the RCS were washed along the surface by the NaCl solution. After neutral salt spray tests for 1000 h, it is worth mentioning that the black trace turned white. Likewise, the RCSs are brighter than before. As observed in Figure 11c, the RSM samples suffered more severe corrosion than 6A01-T5 and the RCS samples. Many corrosive pits and tawny corrosion products are conspicuous in the RSM.

![Figure 11](image-url)

**Figure 11.** Surface appearance of (a) 6A01-T5, (b) the RCS samples and (c) the RSM samples before and after neutral salt spray tests.

Surface morphological characteristics of samples after neutral salt spray tests are shown in Figure 12. As shown in Figure 12a, corrosive pits are conspicuous in 6A01-T5 surface. Moreover, the corrosion products around the corrosive pits are dehiscent and tend to fall off. The surface of 6A01-T5 after neutral salt spray tests for 1000 h is much smoother and largely covered with dense corrosion products. This illustrates that corrosion layers with a protective effect were formed. As depicted in Figure 12b, after neutral salt spray tests were performed for 500 h, more pits and cracks are observed in the surface of the RCS compared with that of 6a01-T5. The corrosion layers have no positive effect to protect the fresh matrix. As corrosion time increases to 1000 h, many dense corrosion products are visible in some areas, and this means that the corrosion process is at a stable stage in which the corrosion of the fresh matrix is inhibited [21–23].

As mentioned above, the RSMs are composed of ferro-silicon and epoxy resin. It is well-known that epoxy resin has excellent corrosion resistance. Hence, corrosion occurred on the ferro-silicon part. Figure 13 shows the surface of the RSM samples after neutral salt spray tests for 1000 h. The holes caused by the detachment of ferro-silicon were well marked in the repaired areas. Furthermore, the substrate in the RSM samples is covered with loose corrosion products and has very bad corrosion morphology. With reference to the reports [24], ferro-silicon in the repaired areas has higher corrosion potentials than the substrate (6A01 aluminium alloy). In this case, galvanic corrosion happened between the...
repaired areas and the substrate. The repaired areas, such as the cathode, were protected, whereas the substrate, such as the anode, corroded dramatically. Therefore, the RSM samples exhibited poor corrosion resistance.

![Figure 12](image1.png)

**Figure 12.** Surface morphology of (a) 6A01-T5 and (b) the RCS samples after neutral salt spray tests.

![Figure 13](image2.png)

**Figure 13.** Surface of the RSM samples after neutral salt spray tests for 1000 h. (a) The repaired areas and (b) the nearby substrate.

3.3.2. Electrochemical Tests

The repaired areas (RSM) do not have continuous conductivity since they are formed by epoxy resin and ferro-silicon. Hence, electrochemical tests cannot be carried out on the RSM. Figure 14 is the open circuit potential ($E_{OCP}$) of samples before and after neutral salt spray tests. As shown in Figure 14a, the $E_{OCP}$ variation of the RCS is similar to that of 6A01-T5. The initial $E_{OCP}$ is at a relatively low level and then increases rapidly. Afterwards the $E_{OCP}$ gradually stabilizes downwards. However, the $E_{OCP}$ of 6A01-T5 fluctuates greatly and is higher in comparison to that of the RCS. In the initial stage of tests, corrosion happened promptly in the surface of samples, and a passive film was formed resulting in the rapid increase in $E_{OCP}$. Then, the variation of $E_{OCP}$ was ascribed to the formation and destruction of the passive film. The $E_{OCP}$ of the RCS has a small fluctuation such that its passive film is more stable. After neutral salt spray tests, the $E_{OCP}$ of 6A01-T5 is still a little higher than that of the RCS. Accordingly, galvanic corrosion happened between RCS and the substrate. The repaired areas, such as the anode, corroded acutely, whereas the substrate areas, such as the cathode, were protected. What is more is that a small increase in $E_{OCP}$ is distinct in the RCS after neutral salt tests for 500 h. That is to say that galvanic corrosion was weakened due to the decrease in $E_{OCP}$ difference between RCS and the substrate.
The potentiodynamic polarization curves of samples after neutral salt spray tests for 500 h and 1000 h are shown in Figure 15, and the related electrochemical parameters are depicted, indicating that the \( E_{\text{corr}} \) of RCS increases to \(-0.926\) V/SCE and \( I_{\text{corr}} \) decreases to \(1.004 \times 10^{-6} \) A/cm\(^2\). Thus, there is a downtrend in corrosion tendency indicating that the corrosion products formed on the surface of the RCS have protective effects. This is according to the analysis above.
The electrochemical results have indicated the occurrence of galvanic corrosion between the RCS and the nearby substrate. In order to prove the fact that RCS protects its nearby substrate by corroding as the sacrificial anode, the surface of the substrate around the RCS after neutral salt tests for 1000 h is shown in Figure 16. As indicated, the substrate around it is almost covered with thin corrosion layers that are smooth. As shown in the magnified image, there are numerous small and shallow pits. By contrast, 6A01-T5 after neutral salt tests for 1000 h shows a more terrible appearance than the substrate around RCS. This also demonstrates that the substrate around it is protected by RCS during the corrosion process. The RCS samples have the lowest rate of mass loss, although the RCSs are sacrificed. This is because the RCSs are small, and the substrate around it corroded slightly in comparison to the 6A01-T5 samples. In addition, Al and Al$_2$O$_3$ in RCS also have excellent corrosion resistance [25–27].

![Figure 16. Surface of the RCS samples after neutral salt spray tests for 1000 h.](image)

In conclusion, the corrosion mechanism of the RCS samples can be described in Figure 17. The RCS samples are immersed in NaCl solution during neutral salt spray tests. As a result, Al is easy to dissolve due to the existence of Cl$^-$. Al$^{3+}$ is formed by the following reaction, which is the anodic reaction.

$$\text{Al} \rightarrow \text{Al}^{3+} + 3\text{e}^-,$$  \hspace{1cm} (2)

Due to the potential difference between the RCS and the substrate around it, the anodic reaction in the RCS is accelerated. Hence, more Al dissolves and more Al$^{3+}$ formed in the RCS. There are still tiny pores, although the tamping of Al$_2$O$_3$ particles decreases the porosity of RCS. Moreover, the cathodic reaction that follows occurs in the gaps between Al and Al$_2$O$_3$ or around the micro-pores [28,29].

$$\text{O}_2 + \text{H}_2\text{O} + 3\text{e}^- \rightarrow 4\text{OH}^-,$$  \hspace{1cm} (3)

$$\text{OH}^- + \text{Al}^{3+} \rightarrow \text{Al(OH)}_3,$$  \hspace{1cm} (4)

Accordingly, the Al region is covered with Al(OH)$_3$, which is close to Al$_2$O$_3$ particles. Subsequently, some Al(OH)$_3$ react with H$_2$O and transformed into Al$_2$O$_3$·nH$_2$O. As corrosion time increases, more and more corrosion products are formed. It is not easy for Cl$^-$ to permeate into the fresh matrix, and this results in its enrichment on the surface. Then, the reaction between Al(OH)$_3$ and Cl$^-$ happens as follows [30,31].

$$\text{Al(OH)}_3 + 3\text{Cl}^- \rightarrow \text{AlCl}_3,$$  \hspace{1cm} (5)

### Table 5. Related electrochemical parameters of samples.

| Materials | $E_{\text{corr}}$ (V SCE) | $I_{\text{corr}}$ (A/cm$^2$) |
|-----------|--------------------------|-----------------------------|
| 6A01      | $-0.883$                 | $8.124 \times 10^{-7}$      |
| RCS       | $-1.006$                 | $1.131 \times 10^{-6}$      |

The electrochemical parameters of samples are summarized in Table 5.
AlCl₃ has a negative effect on the formation of stable corrosion layers and causes the production of holes. The reactions of Equations (2)–(5) also happen in the substrate around the RCS, although these areas are protected. As dense corrosion layers formed and the potential difference between RCS and the substrate around it gradually disappeared, the corrosion reactions were weakened.

![Corrosion mechanism diagram](image)

**Figure 17.** Corrosion mechanism of the RCS samples (a) un-corroded, (b) dissolution of Al, (c) formation of corrosion products and (d) corroded.

4. Conclusions

1. The samples repaired by cold spray have lower porosity and higher tensile strength than the samples repaired by superior metal. The samples repaired by cold spray have met the requirements for mechanical properties.
(2) The samples repaired by cold spray have the lowest rate of mass loss and show better corrosion resistance than 6A01-T5. Its repaired areas will protect the nearby substrate by corroding as the sacrificial anode.

(3) The cold spray process and Al-based powders are applicable for repairing the aluminum alloy components of high-speed trains caused by corrosion.

Author Contributions: Methodology, Z.Z. and C.S.; investigation, P.Z. and X.S.; data curation, S.H. and Z.Z.; writing—original draft preparation, S.H. and X.H.; writing—review and editing, S.H. and T.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (No. 51605070) and Dalian Science and Technology Bureau (2019RQ085).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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