Proc. Schl. Eng. Tokai Univ., Ser. E
39 (2014) 41-48

Corrosion Resistance of Bridge Strands Galvanized with a Zinc-Aluminium Alloy

by

Turki JARWALI [*1], Shunichi NAKAMURA [*2] and Keita SUZUMURA [*3]

(Received on Mar. 18, 2014 and accepted on May 15, 2014)

Abstract

Bridge strands consisting of steel wires galvanized with Zn-Al are expected to have higher corrosion resistance than the Zn galvanized ones. The strands consisting of 19 parallel steel wires galvanized with Al (10%) and Zn (90%) alloy were produced and corrosion acceleration tests were conducted. The anti-corrosion performance was then compared with the conventional strands galvanized with Zn. The strands were kept under three different corrosion environments: kept at a relative humidity (RH) of 60%, kept at a RH of 100%, and wrapped with wet gauze which simulates wet conditions. The strands were kept in the thermo-hygrostat at 40^{o}C for 150 days. The mass loss due to corrosion of the strands galvanized with Zn-Al under the relative humidity of 60% and 100% was small and the strands had sufficient corrosion resistance. Under the wet conditions, the corroded mass of the strands galvanized with Zn-Al was 15 times larger than that under the relative humidity of 100%. The strands galvanized with Zn-Al have less corrosion than those galvanized with Zn under the three environmental conditions. Corroded mass is larger in the surface wire, the inside wire and the center wire in this order. The cross-sections of corroded strands were investigated by a microscope showing that the corrosion product of Zn was loose and easy to exfoliate from the steel layer. On the contrary, the corrosion product of Zn-Al alloy was dense and hard to exfoliate from the steel layer. This difference is the rationale for the superiority of the Zn-Al galvanized wires.

Keywords: Bridge cables, Steel wires strands, Zinc-aluminium alloy, Galvanized wires, Corrosion, Corrosion acceleration tests.

1. Introduction

Cables and hangers of old suspension bridges and stays of cable-stayed bridges have been exposed to severe corrosive environment and often suffer from steel corrosion[1-4]. Some of the bridge wires have been broken, reducing the bridge's load bearing capacity. As the cables are the key structural element for cable-supported bridges, the anti-corrosion measure is essential.

Cables consist of many high strength steel wires, which are almost exclusively galvanized with zinc to improve corrosion resistance. However, galvanized wires seem to be insufficient to prevent corrosion because corrosion problems have occurred in actual bridges. A new technology has been developed for high strength bridge wires to further increase corrosion resistance: steel wires are galvanized with zinc (Zn) and aluminium (Al).

Miyachi, Nakamura and Suzumura carried out experimental studies using Zn-Al galvanized wires and found below [5]. The mass loss of steel wires due to corrosion under the relative humidity of 60% and 100% is much smaller than that under the wet environment, and the amount of corrosion is not much different between Zn-Al galvanized wires and Zn galvanized wires. On the other hand, the mass loss of the steel wires galvanized with Zn-Al is distinctively smaller than those galvanized with Zn under the wet condition. The mass loss of the NaCl attached wires is twice larger than that without NaCl under the wet condition.

A bridge cable consists of parallel wire strands or helical wire strands consisting of many steel wires. Therefore, a further study is required to prove if the above findings with individual wires by Miyachi et al. [5] can be applied to strands consisting of many wires.

*1 Graduate Student, Graduate School of Science and Technology, Course of Science and Technology
*2 Professor, Department of Civil Engineering
*3 Nippon Steel and Sumikin Engineering

In this study the strands consisting of 19 parallel steel wires galvanized with Zn (90%) and Al (10%) alloy are produced and corrosion acceleration tests have been conducted under three different environmental conditions for five months. The same tests are also carried out with the strands consisting of galvanized wires with Zn. Corrosion resistance of the Zn-Al galvanized steel wire strands is clarified by comparing the mass loss due to corrosion of the two groups of steel wire strands galvanized with Zn-Al alloy and those with Zn.

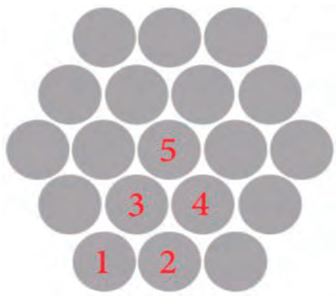
(a) Zn-Al galvanized strands (b) Zn galvanized strands (c) Cross section of a strand

Fig.1 Strands before corrosion acceleration tests

(a) RH=60% (b) RH=100% (c) Wrapped with wet gauze

Fig.2 Three corrosion environments

Fig.3 Thermo-hygrostat (Left: Appearance, Right:Inside)



S (Surface wire): 1-2
I (Inner wire): 3-4
C (Core wire): 5

Fig.4 Arrangement of wires

2. Steel wires galvanized with Zinc-Aluminium alloy

There have been studies on steel plates galvanized with Zn-Al alloy [6]. The relations between the corroded thickness and the Al containment rate in the galvanized layer were found when the steel plates were exposed to different environments for five years [6]. Under the severe marine environment the corroded thickness is highest at the Al rate of 0% (Zn only), decreases until 7%, turns to increase until 20%, and then decreases thereafter. The corroded thickness under the industrial environment is less than that under the severe marine environment but the tendency is almost the same as the marine environment. The corroded thickness at the countryside is further less than the industrial environment.

The Zn and Al alloy is attached to steel wires by the hot-dip method: steel wires go through the tank where these metals are melted. The higher rate of Al requires the higher melting temperature, which affects the mechanical properties of high strength bridge wires. Considering the anti-corrosion properties of Zn-Al steel plates mentioned above and the melting temperature, the rate of Al is decided to be 10% and the melting temperature is set at 460°C which is the same as the conventional zinc galvanized bridge steel wires.

Steel wires with a diameter of 5.0 mm galvanized with Zn (90%) and Al (10%) alloy are produced and bundled in parallel to form a strand for this study. Each wire is 160 mm in length and has a tensile strength with 1665 MPa. The attached Zn-Al alloy is 331 g/m^2, which is equivalent to 50 μm in thickness. Fig.1 shows a steel wire strand galvanized with Zn-Al alloy and that with Zn before the corrosion acceleration tests. The appearances of both strands are not much different. Fig.1 also shows an illustration of the cross section consisting of 19 wires.

3. Wire specimens and corrosion acceleration

The detail of corrosion acceleration tests is explained in this section. The steel wire strands galvanized with Zn-Al alloy and those galvanized with Zn are kept in the same corrosion environments and the mass loss due to corrosion is compared to clarify the corrosion resistance of the Zn-Al alloy galvanized wires against the Zn galvanized wires.

The steel wire strands are tested in three different corrosion environments: (a) they are kept at a relative humidity (RH) of 60%, (b) they are kept at a RH of 100%, and (c) they are wrapped with wet gauze simulating the wet condition. Water and oxygen are necessary to corrode steel, and the wet gauze supplies both. It was proved by the past study that this wet gauze method simulated the corroded steel wire strands in an actual corrosion environment of suspension bridge cables [7), 8), 9)].

It is known that sodium chloride (NaCl) accelerates steel corrosion. The water with NaCl of 0.01% is sprayed to the gauze wrapping the wire strands. This value was decided that the NaCl concentration was about 0.01% in the remaining water inside the main cables of the existing suspension bridges [2), 7)].

The strand specimens are all kept in the thermo-hygrostat at RH of 60% and temperature of 40°C to accelerate corrosion. For the corrosion environment-(a) the wire specimens are placed in a plastic box and kept in the thermo-hygrostat (Fig.2 (a), Fig.3). For the corrosion environment-(b) the strand specimens are placed in a plastic box with a lid and kept in the thermo-hygrostat (Fig.2 (b), Fig.3). Inside the plastic box there is a small case filled with water which makes the inside of the plastic box RH of 100%. For the corrosion environment-(c) the wire specimens are wrapped with wet gauze and are placed in a plastic box with a lid (Fig.2 (c), Fig.3). It is planned that, when the gauze becomes dry, it is sprayed with water. But the gauze was wet for five months and no extra water was sprayed.

There are three strand specimens at each group. Five wires are arbitararily chosen and arranged at the positions indicated in Fig.4 before the corrosion acceleration tests. Mass of these five representative wires is measured before the test starts. One strand specimen at each group is taken out from the thermo-hygrostat in 30 days, another specimen in 90 days, and the last specimen in 150 days. When they are taken out from the thrmo-hygrostat, they are photographed, the corrosion substances are removed from the surface, and then

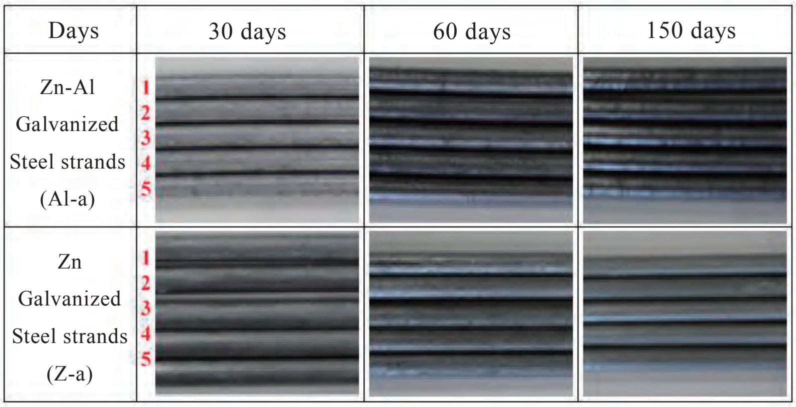


Fig.5 Appearance of corroded representative wires at RH=60%

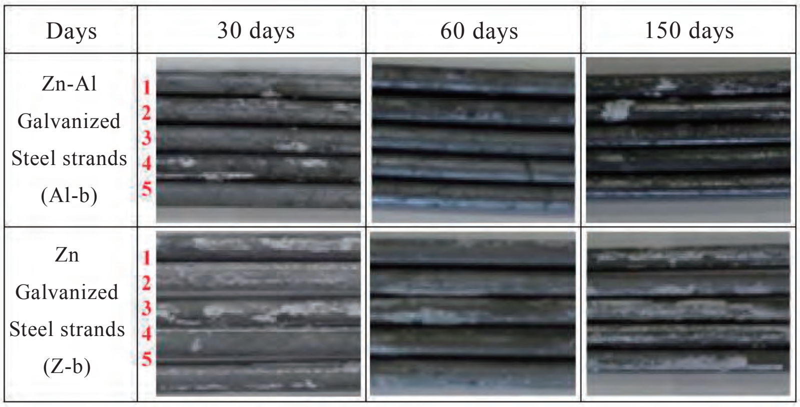


Fig.6 Appearance of corroded representative wires at RH=100%

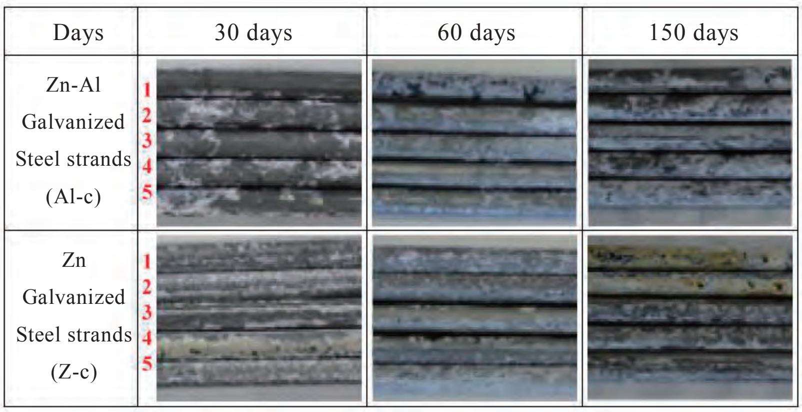


Fig.7 Appearance of corroded representative wires at wet condition

the mass of the representative wires is measured. The removal of corrosion substance was carried out by a metallic sponge with special care so that it did not damage the healthy parts.

4. Corrosion acceleration test results

This chapter shows the results of the corrosion acceleration tests. Fig.5 to Fig.7 show appearances of the five representative wires in the corrosion environment-(a) (RH=60%), the corrosion environment-(b) (RH=100%) and the corrosion environment-(c) (wet condition) in 30, 90 and 150 days since the start of the corrosion acceleration test. Representative wires are chosen from the surface wires (No.1 and No.2) and the inside wires (No.3 and No.4) and the core wire (No.5), as shown in Fig.4.

All of the specimens look healthy and no difference is found between Zn-Al galvanized strands and Zn galvanized strands in Fig.5, the corrosion environment-(a) (RH=60%). In Fig.6, the corrosion environment-(b) (RH=100%), both Zn-Al galvanized strands and Zn galvanized strands corroded more than the corrosion environment-(a). However, corrosion is spread only on the surface layer and no steel corrosion is seen. There is no distinctive difference among five representative wires.

In Fig.7, the corrosion environment-(c) (wet condition), both Zn-Al galvanized strands and Zn galvanized strands corroded severer than the corrosion environment-(b). The Zn-Al galvanized strands are covered with white Zn-Al corrosion. For the Zn galvanized strands, not only the white zinc corrosion but also steel corrosion appear in 150 days. It is understood from Figs. 5 to 7 that both Zn galvanized and Zn-Al galvanized steel strands have sufficient corrosion resistance at RH of 60%. On the other hand, the galvanized layer corrodes more at RH of 100% and the corrosion further accelerates under the wet condition.

Figs.8-13 show the mass loss due to corrosion of the representative wires, which is derived by subtracting the initial mass from the corroded wire's mass. The mass of the corroded wires is measured after the corrosion substances are removed. Figs. 8 and 9 show the mass loss due to corrosion of the surface wire, the inside wire and the core wire of the Zn-Al galvanized strands and the Zn galvanized strands at the relative humidity of 60%. The mass loss of the surface wire and the inside wire is the average of the two wires. The mass loss of the Zn-Al galvanized wires is much less than that of the Zn galvanized wires. The mass loss after 150 days is smaller than that after 90 days in Fig.9. This is because the test strands measured after 90 days and 150 days are different. This mass difference is small and can be thought within an allowable error. There is not much difference in the corroded amount among the surface wire, the inside wire and the core wire, indicating corrosion equally proceeds inside the strand.

Figs.10 and 11 show the mass loss due to corrosion of the surface wire, the inside wire and the core wire of Zn-Al galvanized strands and Zn galvanized strands at the relative humidity of 100%. It is also shown that the mass loss of the Zn-Al galvanized wires is much less than that of the Zn coated wires. There is not much difference in the corroded amount among the surface wire, the inside wire and the core wire. It is reminded that the mass loss due to corrosion at RH=100% is 10 times larger than that at RH=60%.

Figs.12 and 13 show the mass loss of the surface wire, the inside wire and the core wire of the Zn-Al galvanized strands and the Zn galvanized strands under the wet condition. Comparing the corroded mass at the relative humidity of 100% (Figs.10 and 11), the amount of corroded mass of the Zn galvanized strands is about three times larger and that of the Zn-Al galvanized strands is about fifteen times larger, respectively. The corroded mass is larger in the surface wire, the inside wire and in the core wire in this order.

The comparison of the mass loss due to corrosion of the surface wire and the inside wire and the core wire between the Zn-Al and the Zn galvanized strands is shown in Figs.14-16, proving that the Zn-Al galvanized strands are superior to the Zn galvanized strands.

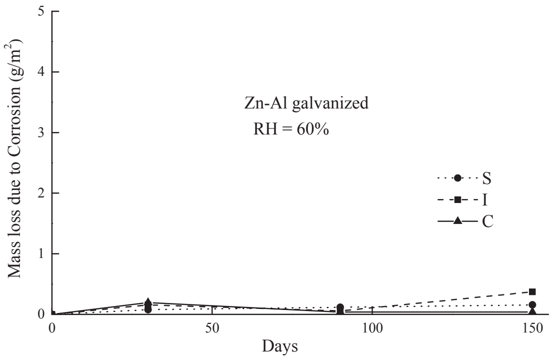


Fig.8 Mass loss due to corrosion of Zn-Al galvanized strands at RH=60% (Al-a)

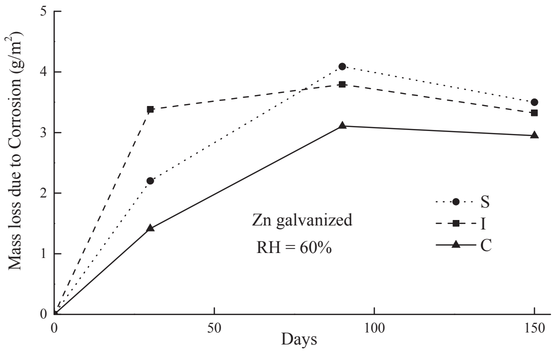


Fig.9 Mass loss due to corrosion of Zn galvanized strands at RH=60% (Zn-a)

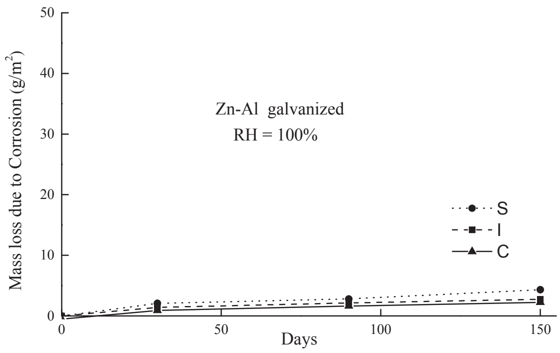


Fig.10 Mass loss due to corrosion of Zn-Al galvanized strands at RH=100% (Al-b)

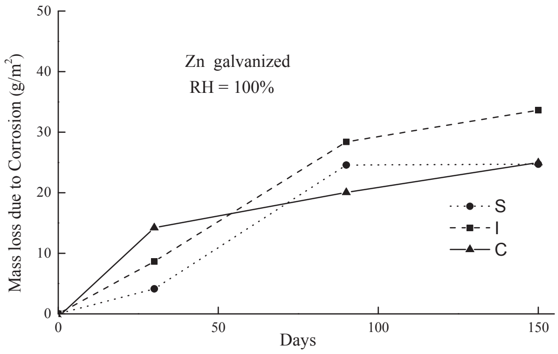


Fig.11 Mass loss due to corrosion of Zn galvanized strands at RH=100% (Zn-b)

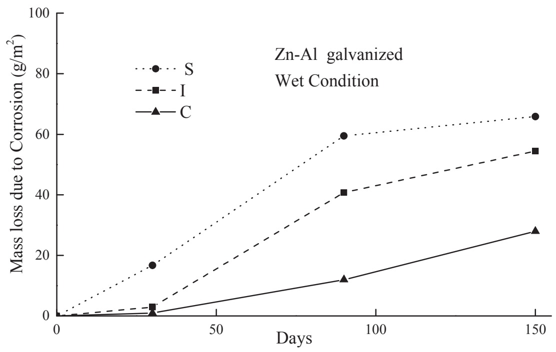


Fig.12 Mass loss due to corrosion of Zn-Al galvanized strands at wet condition (Al-c)

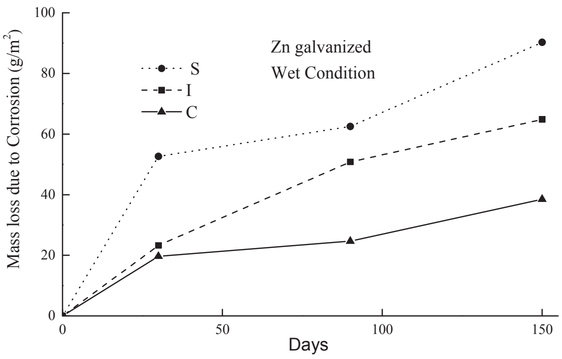


Fig.13 Mass loss due to corrosion of Zn galvanized strands at wet condition (Zn-c)

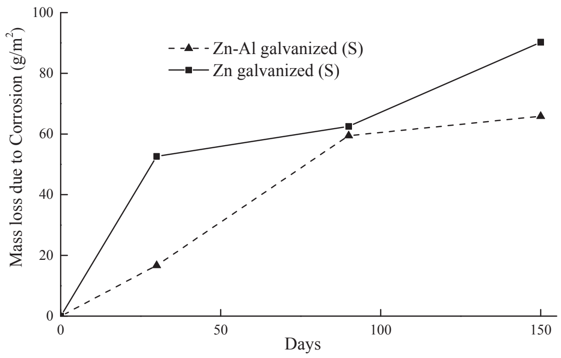


Fig.14 Mass loss due to corrosion of the surface wire

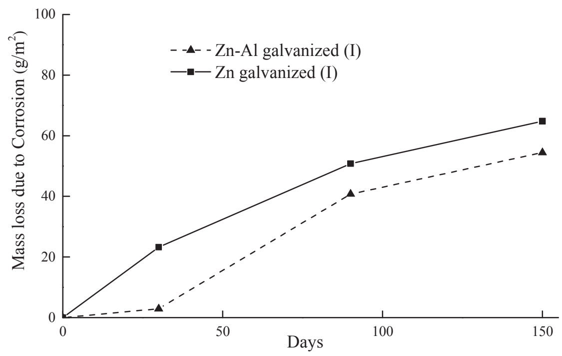


Fig.15 Mass loss due to corrosion of the inside wire

These results of corroded mass loss correspond to the aforementioned appearances of the corroded strands. When strands are placed at 60%, both the Zn-Al galvanized wires and the Zn galvanized wires have sufficient corrosion resistance. When strands are placed at 100%, the Zn-Al galvanized wires have sufficient corrosion resistance but the Zn galvanized wires could not be sufficient. When strands are exposed to the wet condition, the wires severely corrode. The mass loss due to corrosion of the Zn-Al alloy galvanized strands is considerably smaller than the Zn galvanized strands, which validates higher corrosion resistance of the Zn-Al alloy layer.

Let us consider the remaining life of the surface wires which is the most severely corroded wire. Corrosion speed of the surface wire of the Zn galvanized strands at RH=60%, RH=100% and wet condition is 8.40, 80.69 and 216.65 g/m^2/year (=3.50, 33.62 and 90.27 g/m^2 x 12/5). This gives the remaining life of 39.4, 4.1 and 1.5 years until the initial galvanized layer of 331g/m^2 is completely consumed.

Corrosion speed of the surface wire of the Zn-Al galvanized strands at RH=60%, RH=100% and wet condition is 0.89, 10.39 and 158.65 g/m^2/year (=0.37, 4.33 and 65.86

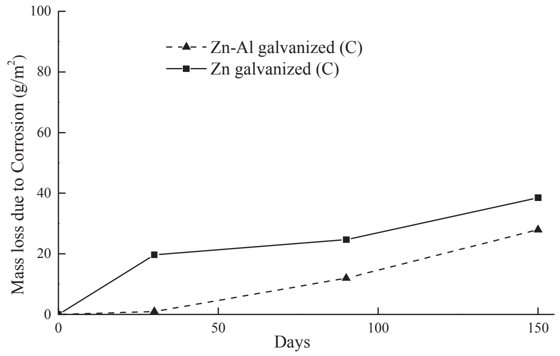


Fig.16 Mass loss due to corrosion of the core wire

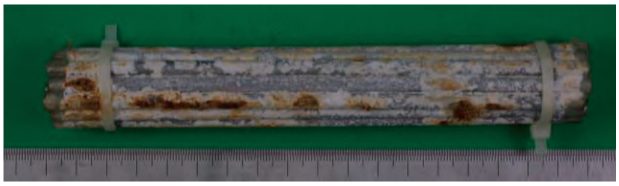


Fig.17 Corroded strand galvanized with Zn

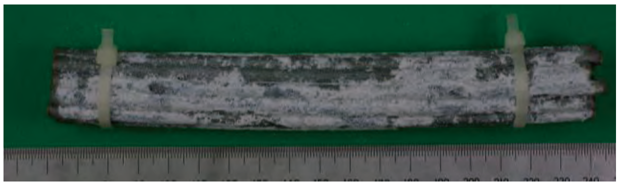


Fig.18 Corroded strand galvanized with Zn-Al

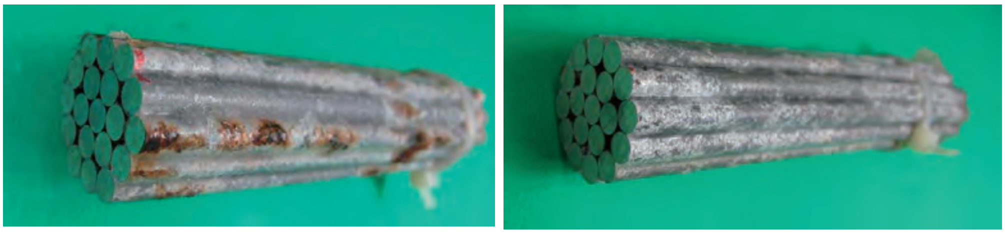


Fig.19 Cut strands galvanized with Zn (left) and galvanized with Zn-Al (right)

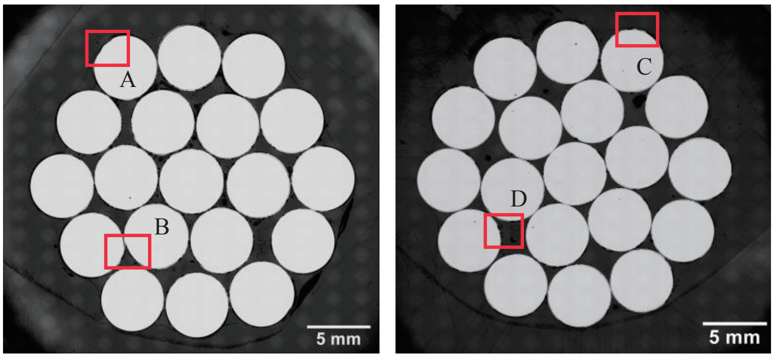


Fig.20 Cut crosssection of Zn galvanized strand (left) and Zn-Al galvanized strand (right)

g/m^2 x 12/5). This gives the remaining life of 371.9, 31.9 and 2.1 years until the initial galvanized layer of 331g/m^2 is completely consumed.

It is reported that the average corrosion speed of galvanized steel plates is 13 g/m^2/year under marine environments. The estimated corrosion speed of the wires at the wet condition is much higher than this because the test was conducted at a very high temperature of 40°C. This consideration on the remaining life also indicates the superiority of the Zn-Al galvanized steel strands.

5. Investigation of corroded wires by a microscope

The corroded strands galvanized with Zn-Al alloy and those with Zn under the wet condition (Al-c and Z-c) in 150 days are investigated by a microscope.

Figs.17 and 18 show appearances of both strands. The Zn-Al galvanized strands are covered with white zinc-aluminium corrosion. On the Zn galvanized strands not only white zinc corrosion but also steel rust appears. These strands were cut into half at the severely corroded positions (Fig.19) and the cross section was investigated. Fig.20 shows the cross sections of both strands shot by an optical microscope. Four areas, part of the surface wires and contact areas between the surface and the inside wires, indicated in Fig.20 (part A, B, C and D) were investigated in detail. These four parts were chosen because corrosion was severe.

Fig.21 shows the surface wire (part A in Fig.20) of the Zn galvanized strand and a close-up of part E, the severest corroded part, is shown at the right. Not only the Zn layer but also the steel layer is partially corroded. As the coating layer is 50 μm in thickness, the boundary of steel and coating can be estimated.

Fig.22 shows the contact areas between the surface and inside wires (part B in Fig.20) of the Zn galvanized strand and a close-up of part F, the severest corroded part, is shown at the right. It is understood that severe corrosion occurs at the intersection of wires. Comparing two groups of photos of Zn galvanized strands, Figs.21 and Figs.22, the surface wire is corroded severer than the inside wire. This is because the surface wire is directly touched with the wet gauze, which is a severer corrosion environment.

Fig.23 shows the surface wire of the Zn-Al galvanized strand and a close-up of part G, the severest corroded part, is shown at the right. Only the Zn-Al layer is corroded and some Zn-Al layer remains. The Zn-Al layer seems dense and hard to exfoliate from the steel layer.

Fig.24 shows the contact areas between the surface and inside wires of the Zn-Al galvanized strand and a close-up of part H, the severest corroded part, is shown at the right. In Fig.23 and Fig.24, Zn corrodes but Fe and Al look healthy in both the surface and inside wires. This is because Al is effective in restricting corrosion.

Summarizing the above results, in some parts of Zn galvanized strands, the Zn layer is depleted and the steel corrosion occurs. In Zn-Al galvanized strands, Al uniformly distributes which makes the Zn-Al layer dense and hard to exfoliate from the steel layer.

6. Conclusion

Strands consisting of 19 parallel steel wires galvanized with Zn (90%) and Al (10%) alloy were produced and corrosion acceleration tests were conducted. The strands were kept under three different corrosion environments: kept at a relative humidity (RH) of 60%, kept at a RH of 100%, and wrapped with wet gauze which simulates the wet condition. The strands were kept in the thermo-hygrostat at 40°C for 150 days. The following findings are obtained.

1) At RH=60% the corroded mass loss of Zn-Al galvanized strands is much less than that of the Zn galvanized strands.

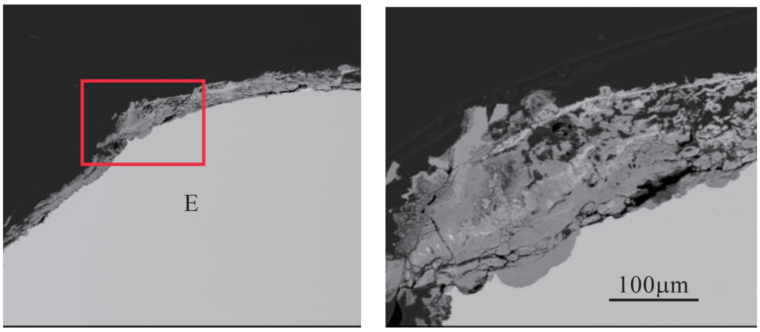


Fig.21 Surface wire of corroded Zn galvanized strand and close-up of Part E

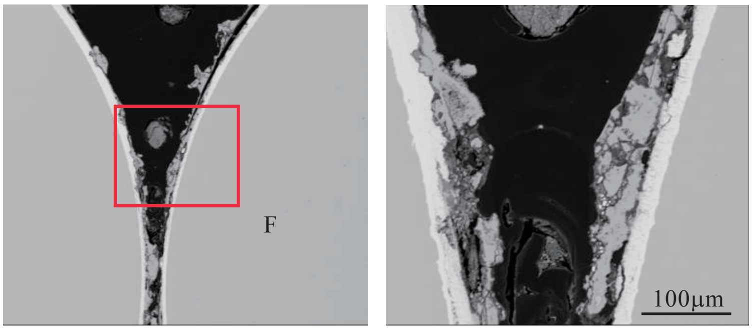


Fig.22 Inner wires of corroded Zn galvanized strand and close-up of Part F

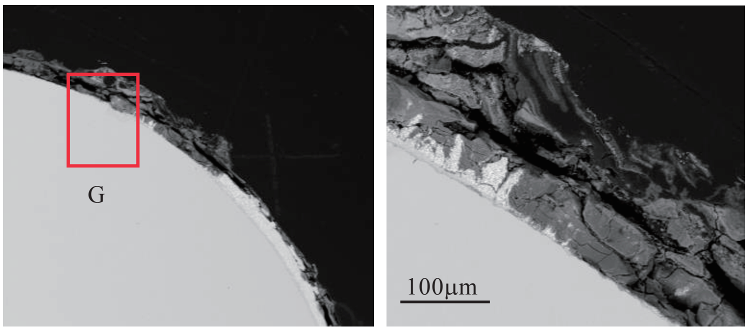


Fig.23 Surface wire of corroded Zn-Al galvanized strand and close-up of Part G

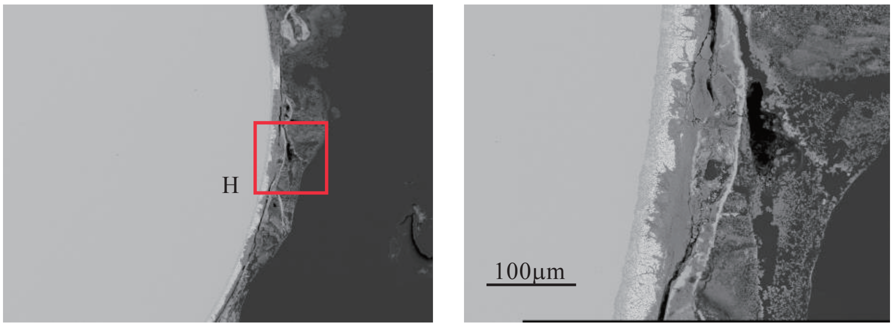


Fig.24 Inner wire of corroded Zn-Al galvanized strand and close-up of Part H

There is not much difference in the corroded amount among the surface wire, the inside wire and the core wire. At RH=100% the mass loss of the Zn-Al galvanized strands is also much less than that of the Zn galvanized strands. There is not much difference in the corroded amount among the surface wire, the inside wire and the core wire. Whereas, the corroded amount at RH=100% is 10 times larger than that at RH=60%.

2) Under the wet condition, the amount of corroded mass of the Zn galvanized strands is about three times larger than that at RT=100%, and that of the Zn-Al galvanized strands is about fifteen times larger than that RH=100%. The corroded mass of the consisting wires of Zn-Al strand is smaller than that of the Zn galvanized strand. Mass loss due to corrosion is larger in the surface wire, the in-side wire and the centre wire in this order. This is because the surface wire is directly touched with the wet gauze, which is a severer corrosion environment.

3) The corroded strands galvanized with Zn-Al alloy and those with Zn under the wet condition in 150 days are investigated by an optical microscope. As for the cross section of the corroded Zn galvanized strands, not only the Zn layer but also the steel layer is corroded in the surface wire. In the inside wire no corrosion of Fe is seen but severe corrosion of Zn spreads overall and its volume expands. It seems loose and coarse and easy to exfoliate from the steel layer. As for the cross section of the corroded Zn-Al galvanized strands, only the Zn-Al layer is corroded and some Zn-Al layer remains in the surface wire and the inside wire. Fe and Al look healthy. The Zn-Al layer seems dense and hard to exfoliate from the steel layer.

4) Summarizing this study, high strength steel strands galvanized with Zn-Al have higher corrosion resistance than the conventional Zn galvanized strands. As there seems no major problem in manufacturing process, it is feasible and promising for bridge strands.

Acknowledgements

The authors would like show their gratitude to Tokyo Rope Co. for supplying the steel wires galvanized with Zn-Al and to Saudi Arabia Embassy for providing research funding to this study.

References

1) F. L. Stahl and C. P. Gagnon: Cable Corrosion, ASCE Press, New York, (1996).

2) R. Betti, A.C. West, G. Vermaas, and Y. Cao: Corrosion and Embrittlement in High-strength Wires of Suspension Bridge Cables, J. Bridge Eng., 10(2), (2005), pp.151-162.

3) K. Furuya, M. Kitagawa, S. Nakamura, and K. Suzumura: Corrosion Mechanism and New Protection of Bridge Cables, Structural Engineering International, Journal of IABSE, 10(3), (2000), pp.189-193.

4) R. Mayrbaurl, and S. Camo: Cracking and fracture of suspension bridge wires, Journal Bridge Eng., 6(6), (2001), pp.645-650.

5) K. Miyachi, S. Nakamura and K. Suzumura: Corrosion Resistance of Steel Bridge Wires Coated with Aluminium-Zinc Alloy, Proceedings of JSCE A, Vol.69, No.4, (2013), pp.691-699.

6) H. Fujii: Aluminum zinc alloy plating steel sheet (in Japanese), Bosei-Kanri, (1983), pp.9-19.

7) K. Suzumura, and S. Nakamura: Environmental Factors Affecting Corrosion of Galvanized Steel Wires, Journal of Materials in Civil Engineering, ASCE, 16(1), (2004), p.1-7.

8) S. Nakamura and K. Suzumura: Hydrogen embrittlement and corrosion fatigue of bridge wires." Journal of Constructional Steel Research, Elsevier, Vol.65, Issue 2, (2009), pp.269-277.

9) S. Nakamura, K. Suzumura, and T. Tarui: Mechanical Properties and Remaining Strength of Corroded Bridge Wires, Structural Engineering International, Journal of IABSE, 14(3), (2004), pp.50-54.