Failure analysis of cracking in aluminum alloy shell of a 220 kV gas insulated switchgear

Baoshuai Du 1, 2, Zhongwen Zhang 1, 2, Shuai Su 2, Xinmei Li 1, Yanjiang Bu 2, Wen Li 2, Dongting Wu 3, *

1 State Grid Shandong Electric Power Research Institute, Jinan 250003, China
2 Shandong Electric Power Industry Boiler & Pressure Vessel Inspection Center Co. Ltd., Jinan 250003, China
3 Key Laboratory of Liquid-Solid Structural Evolution and Processing of Materials, Ministry of Education, Shandong University, Jinan, 250061, China

*Corresponding author e-mail: wudongting@sdu.edu.cn

Abstract. Failure analysis of cracking of a GIS aluminum shell which causes SF₆ gas leak in a 220 kV substation was present. Visual inspection, microstructure observation, chemical composition and mechanical properties characterization were performed to reveal the forming mechanism of the crack. It is found that the crack is located in the region of the aluminum alloy shell that undergone welding repair. The crack is continuous and develops within the weld metal. Detailed investigation reveals that the crack initiates by the defect of lack of fusion in the welding repaired zone. The working stress induced by gas pressure, combined with the residual stress and vibration stress, results in the extension of the crack and the final leaking of SF₆ gas.

Keywords: GIS, crack, failure analysis, aluminum shell.

1. Introduction
Gas Insulated Switchgear (GIS) has gain widespread applications as major substation equipment in electric grid due to highly efficient space saving feature, excellent insulation and interruption performance, and ease of maintenance [1-3]. GIS consists of circuit-breakers, disconnectors and other devices in a confined space that is gas insulated, which shows the characteristic of a compact metal encapsulated equipment.

Being a concealed equipment, effective sealing of the insulated gas is a fundamental requirement to guarantee the safety operation of GIS. However, it is found that gas leaking of GIS occurs due to various reasons and puts threat to the operation of GIS. Thus, it is of importance to focus on the reason of gas leaking and making effective strategies to prevent such defects. Herein, a gas leaking case study is reported, which is caused by cracking of GIS shell. Since such cracking rarely happens in routine practice of GIS operation, it is essential to perform a failure analysis to find the root cause of the cracking and the corresponding effective measure to prevent the occurrence of such defect. A comprehensive investigation of the cracked region and properties of the aluminum shell is carried out. It is hoped that
such failure analysis can facilitate the development of manufacturing process and maintenance strategies of GIS equipment.

2. Visual Examination and Non-Destructive Testing

Gas leakage was detected for a GIS in a 220 kV substation during the operation. According to the document of maintenance, low pressure alarm was reported for the bus gas chamber of a 220 kV substation. After on-site detection, it is found that the gas pressure drop was due to the gas leaking caused by a crack in the aluminum shell.

![Image of the dismantled GIS aluminum alloy shell and the cracking area showing the track of the crack.](image)

**Figure 1.** Image of the dismantled GIS aluminum alloy shell (a) and the cracking area showing the track of the crack (b).

![Digital Radiography (DR) image of the crack.](image)

**Figure 2.** Digital Radiography (DR) image of the crack.

The dismantled GIS equipment is shown in Fig. 1. The shell of the GIS tank was made of aluminum alloy with outer diameter of 638mm, length of 2950mm and thickness of 10mm. Crack is located near the upper part of the saddle weld which joins the hand hole cover with the GIS shell. The crack is curved and develops along the axial direction of the GIS cylinder (Fig. 1(b)). It is approximately 2 cm to the saddle weld. Visual inspection reveals that trace of corrosion, wear and external impact was not detected near the crack. X-ray digital radiation image was taken for the cracking area and the result is shown in Fig. 2. It can be seen that the crack is continuous and develops through the wall thickness of the GIS tank for the whole length.
3. Microstructure observation

The cracked area was sampled according to Fig. 3. Three samples were sectioned perpendicular to the crack and the nomenclature is S1, S2 and S3 respectively, as shown in Fig. 3 (a). S1 and S3 consist both end of the tips of the crack respectively and S2 is sectioned from the middle part of the crack.

Cross-sectional samples of S1, S2 and S3 were grinded, electrolytic polished and chemically etched with 1% HF aqueous solution. The macroscopic view is shown in Fig. 3. It can be clearly observed that all the samples contain two distinct area, divided by the black lines (Fig. 3 (b)). Crack is located in the same middle area for all the three samples and it doesn’t penetrate the wall thickness for S3. The overall view of the samples resembles the morphology of welding joint and the middle part corresponding to the weld metal while the side portion is the base metal and HAZ.

![Figure 3. Overview (a) and cross-sectional view (b) of the samples.](image)

![Figure 4. Optical micrographs of S2: (a) base metal, (b) fusion line, and (c) weld metal.](image)
Metallographic observation reveals that all the samples show the similar microstructure, and the typical optical micrographs of S2 was shown in Fig. 4. Microstructure of the side position of the sample shows elongated grains which is normally formed by the rolling process. The middle part contains equiaxed dendrite. Furthermore, an interface exists between the two area (Fig.4 (b)). This part shows the characteristic of fusion line of welding joint which contains epitaxial growth from the base metal to the weld metal. Thus, combined with the observation of macroscopic view and microstructure characterization, it can be deduced that the middle part of the sample where the crack is located is the welding metal.

Morphology of the crack is shown in Fig. 5. For sample S1 and S2, crack which is through wall thickness can be observed and the crack opening is obvious. For S3, there exists un-cracking part and the crack deflects when the it develops towards the outer wall of the aluminum alloy shell. A relatively flat part of one side of the cracked shell can be found for all the samples, as indicated by the white dot rectangular in Fig. 5. For this region, one side of the crack end shows a small curvature change while the curvature of the other one changes obviously.

![Figure 5. Morphology of the cracks presented in S1 (a), S2 (b) and S3 (c). Top part of the image corresponding to outer wall and the lower part corresponding to inner wall of the shell.](image)

Detailed observation of the crack part is shown in Fig. 6 using the magnified optical micrograph. For the region near the outer wall, all samples show the equiaxial dendrite which is typical for aluminum alloy weld metal. However, for the middle part, one side shows the equiaxial dendrite morphology while the other part shows the elongated grain which is characteristic for the base metal fabricated by the rolling process. Moreover, there is no trace of fusion line between the base metal and the weld metal. Therefore, this region is the lack of fusion defect of the welding joint. This incomplete fusion is a weld discontinuity in which lack of bonding exists between the weld metal and the base metal.
Energy dispersive spectroscopy (EDS) was used to measure the chemical composition of different areas of the cracking part and the result is shown in Fig. 7. Area 2 shows the presence of Al, Mg and Fe. However, for area 1, Si was detected which is normally found in aluminum alloy weld for improving the fluidity of the molten pool and avoiding hot crack[4, 5]. Thus, it can be deduced that Al-Si weld materials is used during the welding process. This further gives evidence that middle part of the crack is the lack of fusion defect.
4. Fractography examination

The metal fracture surface was cleaned using ultrasonic device, and the macro-morphology is shown in Fig. 8. Three distinct areas can be observed, which are middle part, near the outside wall part and near the inner wall part respectively. It should be noticed that for the middle part, different morphology was observed for the two sides. One side of the middle part has a white shiny color while the other side is grey. No obvious plastic deformation was observed for the fractured region. Therefore, it can be deduced that the difference in the color and morphology of the strips is caused by the different microstructure and properties of the material. One side is the cracked base metal, while the other side shows the solidified morphology of the weld metal.

Figure 7. SEM image of the crack (a) and EDS result of area 1 (b) and area 2 (c).

Figure 8. Image of the fracture surface of S2
Figure 9. SEM images of the fracture surface corresponding to the left part of Fig. 8. Middle part (a), transition zone between the middle part and the inner part (b), near the inner wall (c), and near the outer wall (d).

SEM images of the fractography of the fracture surface is shown in Fig. 9. The middle part shows a relatively flat morphology with a few strips. However, for the part near the inner wall, grain structure can be observed, and some area shows the presence of welding pores. The high magnification image of the fracture surface indicates that the sample is fractured along the equiaxial dendrite grain boundary and results in the intergranular fracture morphology.

Figure 10. Microhardness of the weld repair zone
5. Microhardness measurement
Microhardness was tested for the typical sample S2. The tested area located in the middle part and the area near the outside wall. For the middle part, the tested area located on both side of the crack. Microhardness test was performed using load of 100 g, duration time of 15 s and test interval of 0.5 mm. An apparent hardness difference can be observed which is caused by the different microstructure of weld metal, HAZ and base metal. For the welding metal, microhardness of 94 Hv0.1 and 97 Hv0.1 was found for the area near the outside and middle part respectively. However, for the HAZ and base metal, the average value drops to 69 Hv0.1 and 75 Hv0.1.

6. Chemical composition and Mechanical properties of the base metal
Chemical composition analysis shows that the base metal of the aluminum alloy is Mg (4.35), Mn (0.54), Cr (0.11), Si (0.13), Zn (0.01), Cu (0.016), Fe (0.39), Ti (0.011) and Al balance. This composition is in the range of standard 5083 H112 aluminum alloy which is used to fabricate the GIS shell. Tensile test result of the shell is shown in Table 1. Results show both the yield strength, tensile strength can fulfill the mechanical requirement for 5083 H112 material. The fractography of the tensile sample shows the presence of dimples which indicates that the fracture mode is ductile fracture. Thus, the mechanical properties of the base metal are qualified.

| No. | Stipulated non-proportional extension strength Rp0.2 (MPa) | Yield strength Rel (MPa) | Tensile strength Rm (MPa) | Elongation A (%) |
|-----|----------------------------------------------------------|--------------------------|----------------------------|-----------------|
| #1  | 205                                                      | /                         | 303                        | 22.5            |
| #2  | 229                                                      | /                         | 298                        | 21.0            |

7. Discussion
Based on the experimental results of mechanical properties and chemical composition of the aluminum alloy, it can be found that the alloy material of the shell is qualified. Experimental observation of the cracks reveals that the crack happens in the middle part of weld metal with equiaxial dendrite. Microhardness test and micro-zone chemical test also reveals that the crack locates in the repair weld region. The contour of the weld metal indicates that the weldment is fabricated by symmetric welding from both the inner and outer wall. The crack was within the weld metal and not extended to the base metal.

Fractography analysis shows that there exists a bright white zone in the middle part of the fracture surface, which is formed by the lack of fusion defect. Thus, conclusion can be made that the crack occurs in the lack of fusion defect in the repair weld region initially. This region of the shell may undergo damage during the fabrication of the GIS, which is welding repaired. However, the aluminum alloy possesses high thermal conductivity and high expansion coefficient, and unsuitable welding process may cause the happen of lack of fusion between the weld metal and the base metal, especially in the root of the welding joint.

This lack of fusion plays the role of the crack. Once the GIS is in operation, the shell may withstand three kind of stresses. The first one is induced by the gas pressure. The second one is welding residual stress which is caused by the weld metal solidification shrinkage effect and uneven heating and cooling of the welding joint. Moreover, the weld metal and the HAZ exhibit tensile residual stress, which tends to facilitate the growth of the crack. The third force of the joint is caused by the vibration force. It is formed by the alternating current in the conductor, the electromagnetic force of the transformer core and the mechanical force induced by the switch operation. The lack of fusion defect, which plays the role of the initial crack, grows due to the above-mentioned stresses during the operation of GIS. The weld metal consists of primary α-Al and eutectics of α-Al + Si. The weld metal has poor toughness compared with the base metal and the crack tends to extend along the grain boundaries in this region[6, 7]. This results in the growth of crack in the weld metal region and causes final failure of the shell. From the above
analysis, it can be found lack of fusion in the repair weld region of the shell is the root cause of gas leaking. Thus, it is of importance to pay special attention for the welding repair process during fabrication of GIS, especially for the component of aluminum shell.

8. Conclusion
The result of the failure analysis conducted on the leaking GIS leads to the following conclusion:

1) Gas leaking of the 220 kV GIS is caused by the cracking through the wall thickness of the aluminum alloy shell.
2) Metallographic examination and the fractography of the fracture surface indicate that the crack was formed in the repair weld region during the fabrication of the GIS.
3) The repair weld region consisting of equiaxial and eutectic weld metal. Crack of the shell initiates from the lack of fusion defect and extends during the operation of GIS due to the combined effect of working force, residual stress, and vibration force, leading to the final leak of SF$_6$ gas.

Acknowledgments
This work was financially supported by Science and Technology Foundation of State Grid Corporation of China (Contract No. SGZJ0000KXJS1800302, Research on metallic material Selection, Manufacturing, Installation Process for Power Transmission and Transformation Equipment and Nondestructive Detection Method for Components) and Technology Innovation Foundation of Shandong Electric Power Industry Boiler & Pressure Vessel Inspection Center Co. Ltd. (GJ2020-01, Research on sealing technology using Fixture and adhesive bonding without power outage for Gas-insulated Metal-enclosed Switchgear).

References
[1] Q. Khan, S.S. Refaat, H. Abu-Rub, H.A. Toliyat, Partial discharge detection and diagnosis in gas insulated switchgear: State of the art, IEEE Electrical Insulation Magazine 35(4) (2019) 16-33.
[2] P. Billen, B. Maes, M. Larrain, J. Braet, Replacing SF6 in electrical gas-insulated switchgear: technological alternatives and potential life cycle greenhouse gas savings in an EU-28 perspective, Energies 13(7) (2020) 1807.
[3] A. Purnomoadi, A.R. Mor, J. Smit, Spacer flashover in Gas Insulated Switchgear (GIS) with humid SF6 under different electrical stresses, International Journal of Electrical Power & Energy Systems 116 (2020) 105559.
[4] H.Z. Rajani, A. Phillion, A mesoscale solidification simulation of fusion welding in aluminum–magnesium–silicon alloys, Acta materialia 77 (2014) 162-172.
[5] F. Vollertsen, F. Buschenhenke, T. Seefeld, Reduction of hot cracking in laser welding using hypereutectic AlSi filler wire, Welding in the World 52(5-6) (2008) 3-8.
[6] M. Sokoluk, C. Cao, S. Pan, X. Li, Nanoparticle-enabled phase control for arc welding of unweldable aluminum alloy 7075, Nature communications 10(1) (2019) 1-8.
[7] S. Shimizu, E. Yamanaka, H. Okuda, Study on cracking in electron beam welding of A6061 (Al-Si-Mg alloy), Welding international 15(10) (2001) 776-782.