Fracture Analysis on Turbine Intermediate Regulating Valve of an Electric Generator Unit

Tianpeng Wang¹*, Yuqiu Sui², Yunan Wang¹²³, Hongqiang Li¹, Mingcheng Sun¹, Li Dai¹ and Nan Wu¹

¹Electric Power Research Institute of State Grid Liaoning Electric Power Co., Ltd, Shenyang, Liaoning province, 110006, PR China
²State Grid Liaoning Electric Power Supply Co. Ltd., Shenyang, Liaoning province, 110006, PR China
³Liaoning Dongke Electric Power Co., Ltd, Shenyang, Liaoning province, 110006, PR China

*Corresponding author’s e-mail: wtp0619004@gmail.com

Abstract. A turbine intermediate regulating valve fractured in a power plant, and the reasons for the fracture were analysed by using macro morphology observation, mechanical properties test, chemical composition analysis and microstructure observation, such as scanning electron microscopy (SEM) analysis or metallographic analysis. The results indicated that the chemical composition and strength properties were in accordance with the standard requirements, but the elongation after fracture and the impact toughness value were all lower than the required values. Precipitation of σ phase further weakened the matrix and reduced the strength of the structure. Fretting friction and collision appeared between the valve stem and the anti-rotating pin, and additional stress was generated by the reduction of radial clearance between the pin and valve. Then cracks and brittle expansion occurred in the stress concentration areas close to the anti-rotating pin holes and finally fractured.

1. Introduction

A staff member of a power plant carried out the partial stroke activity test of the No. 2 combined steam valve as schedule on the unit 4 in March 2016, (part of the journey activity test once a day, and once a week for the whole trip activity test). He found that jamming occurred in the intermediate pressure regulating valve (8% valve position jamming) and estimated that the jamming location was in the regulating valve (the total journey of the valve is 257.9±1.5mm and the regulating valve’s journey accounted for about 16% of the total trip). Slight oxide skin was discovered on the valve rod after disassembling, whereas the valve bushing remained intact without fracture. After removing the valve cover and lifting out the regulating valve, fracture was found in the stress concentration areas close to the anti-rotating pin holes.

The No. 4 unit in this power plant was put into operation on May 18th, 2015. The steam was reportedly held at a temperature of 600 °C under a pressure of less than 8 MPa. The valve’s fracture site was not affected by external stress during the process of operation. A pin, whose material is 2Cr12NiMo1W1V, was mainly applied to prevent the rotation of the valve disc, and a certain amount of clearance exists between the valve rod and pin. The material of the regulating valve was designed as
a nickel-based high temperature deformation alloy (GH901) [1,2], which is based on Fe-43Ni-12Cr with reinforced element such as titanium, aluminum, molybdenum and a small amount of boron and carbon. The reasons for the fracture were analyzed in this paper through the investigation of the fracture morphology, mechanical properties, chemical composition and microstructure of the material, and some suggestions on the maintenance and management of valves were put forward.

2. Experiment analysis

2.1 Macro morphology analysis
The macro morphology of the regulating valve sent for inspection is shown in figure 1. It can be observed that the fracture position is located in the middle of the stem with anti-rotating pin installed. Further analysis of the macro morphology of the fracture surface is shown in figure 2. Two crack sections can be observed on the fracture surface (named section 1 and section 2, respectively), which have been severely oxidized, suggesting that the fracture surface had been exposed to the environment for a significant period of time. Both of the two crack initiations are located in the center of the contacting area between the pin hole and pin. Figure 2b) indicates the propagation directions of the crack towards the edge and the final rupture regions after the formation of two crack initiations during the operation of the valve stem. A fiber region, a radiation region, and a final fracture region, which were formed centrally outwardly across the fracture, are characteristic of a typical brittle fatigue fracture. The crack initiations of the section 1 and section 2 are not in the same horizontal plane, which has about 20 mm difference in height. The fracture section of the section 1 is generally flat, whereas the cross section of the section 2 has an obvious convex platform. The source areas of section 1 and section 2 have a large number of oxide skins in connection with the pin holes, while no oxide skin is observed at the bottom of the pin holes.

Figure 1. Macro morphology of the regulating valve

Figure 2. Macro morphology of the fracture surface
a) Crack sections picture; b) Crack initiations, propagation directions and final rupture regions
2.2 Chemical composition analysis
A specimen was excised from the valve stem for spectral inspection to determine the chemical composition of the part, and the test execution standard was GB/T 4336-2016. The instrument model was DV-6 quantitative direct-reading spectrometer.

The results of the chemical composition analysis are shown in table 1. The required values of the China Aeronautical Materials Handbook [3] (hereinafter referred as handbook) are also listed in table 1. It can be seen that all chemical components in the fracture valve meet the requirements of GH901. There are no anomalies present in the composition of the valve stem that will be considered contributory to the failure of the part.

| element | Fracture sample | Handbook requirement |
|---------|-----------------|----------------------|
| Ni      | 44.17           | 40.0~45.0            |
| Cr      | 12.33           | 11.0~14.0            |
| Mo      | 6.49            | 5.00~6.50            |
| Ti      | 3.01            | 2.80~3.10            |
| C       | 0.033           | ≤ 0.40              |
| Si      | 0.01            | ≤ 0.50              |
| Mn      | 0.024           | ≤ 0.020             |
| P       | 0.002           | 0.008               |
| S       | 0.004           | ≤ 0.020             |
| B       | 0.191           | ≤ 0.30              |
| Al      | 0.036           | ≤ 0.20              |
| Cu      | 0.191           | ≤ 0.20              |

2.3 Mechanical property analysis

2.3.1 Hardness. The hardness test of the valve’s cross section was carried out by 320HBS-3000 brinell hardness tester. The measured hardness values were 368HB, 374HB and 370HB, respectively. The hardness of the GH901 nickel based high temperature deformed alloy introduced in the handbook is 302-388HB. So it can be concluded that the material’s hardness meets the material requirements, but is close to the upper limit.

2.3.2 Tensile properties at room temperature. Two Φ10 mm rod tensile samples along the longitudinal and transverse directions were sampled respectively from the fracture valve stem. CSS-1120 electronic universal testing machine was applied to measure the room temperature tensile properties, and the results are listed in table 2, along with the standard values of the tensile properties for the GH901 alloy written in the handbook. It can be seen that all the tensile strengths and yield strengths along the valve’s two directions meet the standard requirement. Brittle intergranular fracture can be observed along the fracture section, and almost no necking appears. The elongation and contraction of the cross sectional area are far lower than the required value.

| No. | Tensile strength (N/mm²) | Yield strength (N/mm²) | Elongation (%) | Reduction in area (%) | Remark |
|-----|--------------------------|------------------------|----------------|-----------------------|--------|
| 1   | 1194                      | 961                    | 7.0            | 7.84                  | longitudinal |
| 2   | 1204                      | 949                    | 8.0            | 9.75                  | longitudinal |
| 3   | 1153                      | 946                    | 2.0            | 3.96                  | transverse |
| 4   | 1156                      | 964                    | 3.6            | 3.96                  | transverse |
| Standard value | ≥1130 | ≥810 | ≥9% | ≥12% | — |

2.3.3 Impact performance. Three U-notched impact specimens were sampled from each of the longitudinal and transverse directions. NI300C pendulum instrumented impact tester was used and the results were listed in table 3. It is required in the handbook that the impact energy of the GH901 alloy is not less than 56J, but the actual impact energy of the 6 u-notched samples is far below the requirement.
| Sampling direction       | Impact energy/J |
|-------------------------|-----------------|
| Longitudinal direction  | 12.0; 11.1; 11.0|
| Transverse direction    | 6.9; 6.5; 7.7   |

2.4 Mechanical property analysis

A sample was taken at the source of the crack for microscopic examination, as shown in figure 3-5. It can be seen that both the crack initiation and the matrix are twin austenite, but the grain size is large, which can be classified as grade 3 in accordance with GB/T 6394-2002. It can be seen from figure 3 that there is a serious oxidation phenomenon at the location of the crack source. The thickness of the oxide layer is about 100μm, and there are microcracks extending along the grain boundaries.

To further investigate the microstructure distribution of the corrosion zone, a SEM observation of the area around the corrosion layer is shown in figure 4. It can be seen that the corrosion zone has a multi-layered structure: the oxide skin is divided into two layers (layer 4 and layer 5), and the total thickness is about 0.2mm; an oxidation film (layer 3) with no more than 50μm can be seen close to the layer 4; a transition layer (layer 2) with a thickness of 30-50μm exists between the oxidation film (layer 3) and the valve substrate. Energy disperse spectrum (EDS) analysis was carried out at different regions marked in the figure 4, and the result is shown in table 4. The EDS results shows that O, Si, V, Cr, Mn, Fe, Ni, Mo, W and other elements are detected in the oxide skin close to the pin side (layer 5), but only three elements such as O, Cr, Fe can be detected in the oxide layer (layer 4). Considering that the pin material is 2Cr12NiMo1W1V, it is inferred that the oxide skin near the pin side is constituted by the oxidation of the pin material remaining and sticking to the inner surface of the pin hole during operation. More O element can be detected at layer 3, which is further confirmed as the oxide film. The EDS analysis of transition layer and substrate (positions 2 and 1) shows that the elements of the transition layer and substrate are the same.

![Figure 3. Metallographic structure around the crack initiation](image)

![Figure 4. SEM picture of the area around the corrosion layer](image)

| Position | Element content (weight %) |
|----------|-----------------------------|
|          | O   | Si  | V   | Cr  | Mn  | Fe  | Ni  | Mo  | W   | Ti  |
| 1        | —   | —   | —   | 13.51 | —   | 31.56 | 35.30 | 5.20 | —   | 2.41 |
| 2        | —   | —   | —   | 12.77 | —   | 32.97 | 36.29 | 5.80 | —   | 2.32 |
| 3        | 15.80 | —   | —   | 18.65 | 1.02 | 20.55 | 27.21 | 8.72 | —   | 4.14 |
| 4        | 13.31 | —   | —   | 0.65  | —   | 89.04 | —   | —   | —   | —   |
3. Discussion

The mechanical performance test result shows that the chemical component and tensile strength of the failure valve meet the standard requirements. However, the elongation and impact toughness values are far below the required value. Brittle intergranular fracture can be observed along the tensile and impact fracture section, and the material’s toughness is very poor. Macro morphology observation indicates that the crack originated from the position of both sides of the valve’s center close to the anti-rotating pin and expanded outward. The section is rough and there is no obvious plastic deformation, indicating a typical brittle fracture[4]. Microstructure investigation shows that the microstructure of the valve is large twin austenitic, and precipitations appear, further weakening the substrate and reducing the strength of the component[5,6].

The component was run under the condition of 600 ℃ for a long time, the valve stem material elongation decreased significantly because of the existence of the GH901 material’s aging embrittlement[7]. There are a lot of microcracks on the inner surface of pin hole close to the crack source, and the cracks have extended along the grain boundary to the inside of the valve and have penetrated the entire diffusion layer. There are a large number of oxide skins accumulated in connection with the pin holes, while no accumulated or peeling oxide skin is observed at the bottom of pin holes. So we can know that there was a strong interaction force between the pin and the valve. The stress mainly comes from two aspects[8]: firstly, the pin is mainly used to prevent the rotation of the valve, therefore, micro friction is generated inevitably between the pin and the valve rod in the running process. The material strength decreases under high temperature, especially for the 2Cr12NiMo1W1V[9]. Then the two contacting parts produced caking phenomenon because of the micro friction. The caking part produces adhesive particles, which are more easily oxidized under high temperature condition. With continuous operation of the unit, more and more adhesive oxidations accumulate. When the adhesive oxidations reach a certain thickness, they no longer produce a bond phenomenon due to the poor binding force. Secondly, the designed maximum assembly clearance between the pin and valve is 0.05mm, which will become smaller at high temperature due to the expansion of the pin and valve[10]. As the thickness of the adhesive oxidation increases, the clearance may be completely eliminated, causing the pin to bite to death in the pin hole. Thus a considerable expansion force is generated between the pin hole and valve stem. As that the material’s toughness is very poor, and the constraint force on the edge is less than that in the core, micro cracks generate in the center of pin hole when the expansion stress reaches a certain extent. Then the crack sources initiate on the both sides. With the continuous oxidation along the grain boundary and the collision between the valve stem and the anti-rotating pin, the crack can be expanded and even cracked.

To sum up, supervision job should be done strictly by the power plant during the process of the valve’s producing, assembly, inspection or test. The quality of the assembly should be specifically considered. The problem should be eliminated in the germ state, thus a good quality can be ensured. In addition, the inspection and maintenance of the intermediate regulating valve should follow the correct and reasonable maintenance process during the process of maintenance.

4. Conclusion

1) The fracture mechanism of the intermediate regulating valve belongs to brittle fracture;
2) The chemical composition and tensile strength of the valve meet the standard requirements, whereas the elongation and impact toughness are all lower than the required values;
3) Fretting friction and collision between the valve stem and the anti-rotating pin, additional stress generated by the reduction of radial clearance between the pin and valve, and lower plastic toughness account for the crack formation, extension and final fracture of the valve.
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