Discussion on Supervision and Inspection Method of High Temperature Bolt of Steam Turbine

Chengchuan Tian, Chong Jiang, Zhiwei Gao and Hai Zhao*
Huadian Electric Power Research Institute Co., LTD, Hangzhou, Zhejiang, 310030, China
*Corresponding author’s e-mail: chengchuan-tian@chder.com

Abstract: Based on the failure analysis of high-temperature bolts in a thermal power plant, this paper proposed that the fracture mechanism of high-temperature bolts is mainly creep fracture. According to the bolt replacement and rejection criteria, the effectiveness of the current bolt supervision and inspection method was analyzed. It was proposed that the power station should strengthen the creep deformation measurement at the thread of the high-temperature bolt part, not just the screw part.

1. Introduction
A power plant unit #1 has accumulated about 70,000 hours of operation. During the repair, it was found that the high-pressure main valve bolts, medium pressure main valve bolts, high pressure governor valve bolts, medium pressure governor valve bolts, superheater safety valve bolts, and high-pressure steam pipe cylinder flange bolts were broken. The number of bolts, materials, specifications, and the number of broken bolts found in inspection are shown in Table 1. Four representative bolts were tested and analyzed, and the names, design materials and specifications of these 4 bolts are shown in Table 2.

| Serial number | Name                             | Texture of material | Specifications | Number | Crack |
|---------------|----------------------------------|---------------------|----------------|--------|-------|
| 1             | High pressure main steam valve bolt | 20Cr1Mo1VTiB        | M56            | 32     | 8     |
| 2             | IP main stop valve bolts         | 20Cr1Mo1V1          | M56            | 32     | 2     |
| 3             | High pressure governor valve bolt | 20Cr1Mo1VTiB        | M56            | 48     | 5     |
| 4             | Middle pressure governing valve bolt | 20Cr1Mo1V1          | M42            | 32     | 7     |
| 5             | Flange bolt of high pressure steam pipe | 25Cr2MoV        | M48            | 32     | 1     |
| 6             | Superheater safety valve bolt    | 20Cr1Mo1VTiB        | M36            | 48     | 2     |

Table 2. Test bolt information

| Serial | Name                             | Texture of material | Specifications | Form of damage |
|--------|----------------------------------|---------------------|----------------|----------------|
2. Test and analysis

2.1. Fracture morphology analysis
All broken or cracked bolts were broken at the root of the first thread (as shown in Figure 1 and Figure 2). The fracture morphology of the completely broken bolt is shown in Figure 3 and Figure 4. The surface of the fracture was oxidized to turn black, the section was rough, and cracks were visible, but there was no obvious fatigue expansion. The crack was generated from the root of the first thread, and developed from outside to inside, and from one side to the other. The final shear fracture zone was at the bolt center hole (bolts with a center hole, Figure 3) or on the opposite side of the crack source (bolts without center hole, Figure 5). For partially cracked bolts, after the bolt was broken along the crack, the fracture was obviously divided into two parts (as shown in Figure 4 and Figure 6). The morphology of the old fracture was the same as that of the completely broken bolt, and the surface of the fracture was oxidized to black, the section was rough, crack direction is visible, but there was no obvious fatigue expansion shell pattern. The fracture morphology of the bolts all had creep fracture characteristics.

| number | High pressure main steam valve bolt | 20Cr1Mo1VTiB | M56 | Completely disconnected |
|--------|-----------------------------------|---------------|-----|-------------------------|
| 1      | High pressure main steam valve bolt | 20Cr1Mo1VTiB | M56 | Partial cracking        |
| 2      | Middle pressure governing valve bolt | 20Cr1Mo1V1    | M42 | Completely disconnected |
| 3      | Flange bolt of high pressure steam pipe | 25Cr2MoV      | M42 | Partial cracking        |

Figure 1. #1 bolt fracture location  
Figure 2. #4 bolt cracked part  
Figure 3. #1 bolt fracture  
Figure 4. #2 bolt fracture  
Figure 5. #3 bolt fracture  
Figure 6. #4 bolt fracture
2.2. Metallographic organization

The fractured bolts were subjected to metallographic inspection, and the metallographic structure of the base of bolts #1 and #2 were all tempered bainite, as shown in Figure 7. Figure 7 is the base structure of #1 high pressure main valve bolt. The metallographic structure of the bolts #3 and #4 were tempered sorbite, and there was no obvious black net-like austenite grain boundary. The metallographic structure was normal, as shown in Figure 8. Figure 8 is the base structure of medium-pressure governor bolt #3.

The surface of the bolt perpendicular to the section at the source of the crack was prepared for metallographic inspection. There were obvious chain-shaped creep pores distributed along the grain boundary near the fracture of the two high-pressure main valve bolts #1 and #2, as shown in Figure 9 and Figure 10. Obvious creep microcracks distributed along the grain boundary can be seen near the fracture of the two bolts #3 and #4, as shown in Figure 11 and Figure 12.

The metallographic examination results show that the fracture mechanism of the above four bolts is creep fracture.

![Figure 7. #1 bolt matrix organization 400×](image)

![Figure 8. #3-bolt base organization 400×](image)

![Figure 9. #1 bolt creep hole 200×](image)

![Figure 10. #2 bolt creep hole 400×](image)

![Figure 11. #3 bolt creep hole 200×](image)

![Figure 12. #4 bolt creep hole 400×](image)

2.3. Chemical composition analysis

Table 3 shows the chemical composition test results of 4 bolts. The material of 2 high pressure main valve bolts (#1, #2) was 20Cr1Mo1VTiB, which was consistent with the design material. The design material of the medium-pressure speed regulating valve bolt (#3) was 20Cr1Mo1V1, and the material was tested to be 25Cr2MoV, which did not match with the design material. The material of the flange bolts (#4) of the outer cylinder of the high-pressure guide tube cylinder was 25Cr2MoV, which was consistent with the design material.

| Serial number | C    | Si   | Mn   | P    | S    | Cr   | Mo   | V    | Ti   | B     |
|---------------|------|------|------|------|------|------|------|------|------|-------|
| #1            | 0.20 | 0.53 | 0.54 | 0.010| 0.003| 1.08 | 0.81 | 0.56 | 0.20 | <0.0003|

Table 3. Test results of bolt chemical composition
2.4. Hardness inspection

Brinell hardness test was performed on 4 broken bolts. The test results are shown in Table 4. Among the 4 bolts, the hardness of 3 bolts was lower than the lower limit of the standard (compared with the actual material of the bolt). There was no bolt with high hardness (exceeding the upper limit of the standard).

| Serial number | Texture of material | Specifications | HBW  | Test result |
|---------------|--------------------|----------------|------|-------------|
| #1            | 20Cr1Mo1VTiB       | M56×270        | 244  | unqualified |
| #2            | 20Cr1Mo1VTiB       | M56×270        | 248  | unqualified |
| #3            | 20Cr1Mo1V1 (Measured as 25Cr2MoV) | M42×270 | 229  | unqualified |
| #4            | 25Cr2MoV           | M56×270        | 265  | qualified   |

2.5. Room temperature impact test

Table 5 shows the results of the bolt impact test at room temperature. Among the 4 bolts, the impact values of 3 (#1, #2, #4) were lower than the lower limit of the standard. Only bolts #3 (medium pressure speed regulating valve bolts) were qualified according to the actual material (25Cr2MoV).

| Serial number | Texture of material | KU2 (J) | ak (J / cm²) | Test result               |
|---------------|--------------------|---------|--------------|---------------------------|
| #1            | 20Cr1Mo1VTiB       | 34      | 43           | unqualified               |
| #2            | 20Cr1Mo1VTiB       | 52      | 65           | unqualified               |
| #3            | 20Cr1Mo1V1 (Measured as 25Cr2MoV) | 50     | 63           | Qualified (25Cr2MoV)      |
| #4            | 25Cr2MoV           | 24      | 35           | unqualified               |

2.6. Tensile test at room temperature

Tensile tests were performed on 4 bolts. The test results are shown in Table 6. The performance of samples #1 and #2 were qualified, the strength indexes of two samples #3 and #4 were qualified, but the plasticity index was close to or slightly lower than the lower limit.

| Serial number | Rm (N/ mm²) | Rp0.2 (N/ mm²) | A (%) | Z (%) |
|---------------|-------------|---------------|-------|-------|
| #1            | 845         | 750           | 16.5  | 60.5  |
| #2            | 830         | 740           | 16.0  | 62.0  |
| #3            | 875         | 790           | 15.5  | 58.0  |
| #4            | 855         | 740           | 14.5  | 46.5  |
3. Analysis of the cause of bolt fracture

The fracture mechanism of the four bolts is creep fracture. The material of two bolts #1 and #2 is 20Cr1Mo1VTiB, the material of two bolts #3 and #4 is 25Cr2MoV, and the material of bolt #3 is one grade lower than the original design material (20Cr1Mo1V1).

The working temperature of the bolts was about 540°C, that is, the bolts are used in a creep environment, and there is a high stress concentration at the root of the first thread of the bolt. This part will form creep holes or creep micro-cracks after long-term operation at high temperature. These creep holes or creep micro-cracks will develop from the center of the bolt to the outside and eventually lead to fracture.

Creep rupture, like mechanical fatigue fracture, is also composed of the three processes of crack formation, development, and final fracture, but the fracture morphology is different from mechanical fatigue fracture. The creep fracture is usually oxidized to black, and cracks are visible, but there is no fatigue expansion shell pattern. The final fracture area is small, and the plastic deformation of the fracture is not obvious. Macroscopically, it is easily misjudged as a one-time brittle fracture.

Creep fracture at the root of the first thread of a high-temperature bolt is the most common form of damage. The unit #1 has only 70,000 hours of cumulative operation. A large number of fractures and failures occurred in the high-pressure main valve bolts and the medium-pressure governor valve bolts. The reason should be found from the bolt assembly process and bolt material performance.

Excessive pre-tightening of bolts during installation is an important factor that accelerates its creep failure. Because the bolts of the tension connection have the characteristics of uniform force transmission and high rigidity, when the external load is less than the tightening force of the bolts on the same flange, the stress they bear is not the same, which leads to the bolts with high tight force on the same flange creep and fail prematurely.

Under the same load condition, the bolt material properties (strength and toughness) determine its creep life, and the better strength and toughness make it have a higher resistance to creep rupture. The bolt #3 material is one grade lower than the original design material, and insufficient strength is the main reason for its premature failure. The hardness and toughness of the other three fractured bolts are generally low. Among them, the hardness and impact toughness of high-pressure main valve bolts #1 and #2 are lower than the lower limit of the standard, and the plasticity index of the bolt #4 tensile test is lower than the lower limit of the standard. In addition, it can be seen from the on-site hardness test results of the high-pressure main valve bolts that the hardness range of all 32 bolts is between 248 HB -261HB, and the qualified range is between 248 HB -277HB. Among them, the hardness of 20 bolts is close to the lower limit of the standard (248 HB -255HB), accounting for 62.5% of all bolts, showing that although the bolt hardness is qualified, it is generally low. There are two reasons for the low hardness and toughness of bolts. One is the poor material strength and toughness of the bolt itself, and the other is that the long-term operation of the bolt under high temperature causes its strength and toughness to decrease. The poor material strength and toughness of the bolt itself may be an important factor for its premature failure.

4. Discussion on supervision and inspection methods of in-service high temperature bolts

Bolts will gradually age after long-term operation under high temperature. There are many failure modes. According to the failure mechanism of bolts, they are divided into thread seizure, joint surface leakage, material thermal brittle aging, creep, fatigue, center hole burn and stress corrosion, etc. There are the following six criteria for the rejection of bolts: bolts with a lifetime consumption rate of 100% calculated based on operating time, bolts with a residual elongation rate of 100%, bolts with cracks found, bolts with serious damage in appearance that cannot be repaired, and center holes locally burned to melted bolts. The most common failure form of high temperature bolts in thermal power units is creep rupture. Therefore, the supervision and inspection of in-service high temperature bolts should focus on the inspection of creep damage.

On-site bolt inspection methods mainly include the following: appearance inspection, non-destructive inspection (ultrasonic, magnetic particle, staining, endoscopic observation of the
center hole), metallographic inspection, hardness measurement, and creep deformation measurement. According to the bolt rejection standard and the common creep failure mechanism of high temperature bolts, the effectiveness analysis of the bolt field inspection method after operation is as follows:

1. Macro inspection, visual inspection, or magnifying glass inspection, people should focus on inspecting whether there is a crack at the root of the first thread. These methods are simple and easy to implement, which have low technical content and high detection rate.

2. Non-destructive inspection (ultrasonic flaw detection or coloring inspection), these inspectors need to have corresponding inspection qualifications, a certain technical content, and a high detection rate of macro crack defects.

3. Metallographic inspection. On-site metallographic inspection is mainly used to inspect whether the bolt material structure is coarse or whether there are black meshed austenite grain boundaries for 25Cr2MoV, 25Cr2Mo1V steel bolts. For example, 25Cr2MoV steel bolts should be replaced if there are obvious black net-like austenite grain boundaries. Because on-site metallography can only inspect the polished rod part or end of the bolt, and cannot inspect the thread root, the metallographic structure can only be used as a reference index for evaluating material properties, and it is usually invalid for evaluating the creep damage of high-temperature bolts.

4. Hardness measurement. Hardness can indirectly reflect the strength and toughness of the material. Lower hardness means lower strength, and higher hardness indicates that its toughness may be poor. Therefore, DL/T439-2006 thermal power plants are tight at high temperature. The firmware technical guidelines have upper and lower limits on the hardness of bolts of various materials. For example, if the hardness of 25Cr2MoV steel bolts exceeds HB300, they should be replaced. But there is no correspondence between hardness and creep damage. The bolt hardness value can only be used to indirectly evaluate its material properties, but it cannot be used to evaluate the degree of bolt creep damage.

5. Bolt creep elongation measurement, DL/T439-2006 “Thermal Power Plant High Temperature Fastener Technical Guidelines” stipulates that the bolt length should be measured before new bolts are used (and specific measurement methods are specified), and each subsequent major repair should measure the creep deformation of 1/3 bolts. The creep elongation measurement of high temperature bolts is very effective for judging the creep damage.

The safe operation of high-temperature bolts has always been attached great importance. DL/T439-2018 “Thermal Power Plant High-Temperature Fasteners Technical Guidelines” have detailed regulations on the inspection of bolts after operation and the replacement and scrapping of bolts. Power station metal supervisors basically formulate bolt overhaul inspection plans according to this standard. However, there are still deviations in specific implementation. For example, the most used methods for supervision and inspection after high-temperature bolts are macroscopic inspection, hardness measurement, non-destructive inspection (ultrasonic testing or surface coloring) and metallographic inspection, and creep elongation is rarely arranged. This is very detrimental to the creep damage supervision of high-temperature bolts after operation. For example, 8 of the 32 bolts of the main valve of unit #1 were broken, and the remaining 24 bolts with no cracks were inspected on site: the chemical composition is qualified, the metallographic structure is normal, and the hardness is qualified (although most of the bolts have low hardness, it is still slightly higher than the lower limit of the standard). There was no bolt length measurement record before. Therefore, it is impossible to determine whether the 24 bolts need to be replaced according to the on-site inspection results. The bolts must be sampled and identified, which often takes a long time.

The measurement of bolt creep elongation has a strong continuity, and bolt operation supervisors need to do this management work carefully. For power plants that have not carried out this work, it is recommended to strengthen this work in the future, especially for the smaller size bolts of the main valve and speed control valve. Before new bolts are put into operation, a bolt length file should be established, and the in-service bolts should be combined with size and repair to gradually establish a complement bolt length file. DL/T439-2018 “Thermal Power Plant High-Temperature Fasteners Technical Guidelines” stipulate that the creep elongation of the bolt screw part is measured. As the
thread root will produce more than the screw part, and severe creep damage and measuring the full length of the bolt is easier than measuring the screw part, it is recommended to measure the full length of the bolt (including the threaded part at both ends).

5. Conclusions and recommendations

5.1 The fracture mechanism of 4 bolts is creep fracture.

5.2 The creep rupture of bolts in advance may be related to the excessive pre-tightening stress of individual bolts and the low performance of the bolt material itself (creep rupture resistance). Bolt #3 material is one grade lower than the original design may be the main reason for its premature failure.

5.3 The method of supervision and inspection of high temperature bolts should be based on appearance inspection, non-destructive inspection (ultrasonic inspection or color inspection) and creep elongation measurement, supplemented by metallographic and hardness inspection.

5.4 At present, the creep elongation measurement method is rarely used in the supervision and inspection of power station bolts, and the creep elongation is very effective in determining the creep damage of high-temperature bolts. The power station should strengthen this inspection work in the future. New bolts should establish bolt length files before they are put into operation. In-service bolts should be combined with large and small repairs to gradually establish complementary bolt length files, which is necessary for future creep monitoring of bolts.

5.5 DL/T439-2018 “Thermal Power Plant High-Temperature Fastener Technical Guidelines” stipulate the measurement of the creep elongation of the bolt screw part. As the thread root will produce more than the screw part, and severe creep damage and measuring the full length of the bolt is easier than measuring the screw part, it is recommended to measure the full length of the bolt (including the threaded part at both ends).

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