Failure analysis of low-carbon steel pipe clamp of pressure pipe

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Abstract. A real case of breakage of several pipe clamps used in the pressure pipe hanger is investigated. In order to examine the cause of failure, various techniques, including element analysis, mechanical testing, optical and scanning electron microscopy, component analysis, and impact testing were used. It was found that the fractures of the pipe clamps occurred at the transition zone between a straight and arc segments, the finite element analysis has shown that the transition had the highest stress concentration. The surface deformation during pipe clamp manufacturing process caused hardness rising and toughness descending, resulting in surface cracks. Under the combined effect of lower ambient temperature and service stress, the surface cracks expanded rapidly and the pipe clamps fractured finally. Improvements in the molding process and the use of appropriate quality control measures can eliminate this problem.

1. Introduction

The uninterrupted power supply from a power plant mainly depends on the continued functioning of its equipment and components. Proper functioning of boiler tubes, super heater, heat exchanger, etc., is important for maintaining the power supply. Even a single component failure can lead to the abnormal shutdown of the entire power generation system [1-3]. Boiler components are mainly made of steel, cast iron, stainless steel, and high-temperature alloy. Failure of boiler components is a very common phenomenon in a power plant.

This work reports the failure of the pipe clamps used for fastening the pressure pipeline. In January 2018, an electric power engineering company discovered a sudden breakage of the pipe clamps during the installation of the pressure pipeline. The safety of construction workers was threatened. The fracture location was in the transition from arc to straight, as shown in figure 1(a) and 1(b). According to the design information, the pipe clamp material is Q235B, which pertains to low carbon steel and is clearly defined in Chinese standard GB/T 700-2006. Its outer diameter and thickness of the pipe clamp are 1020 and 18mm, respectively. The medium in the pipe is cooling water, the operating temperature is 12°C. After about 200 days of service, the pipe clamps were broken before the medium was used. In order to examine the causes of failure, various techniques including visual inspection, chemical analysis, optical microscopy, scanning electron microscopy and energy dispersive spectroscopy were carried out.
2. Experimental
Background information related to the manufacturing process and the material of the clamps was provided by the manufacturer. The main manufacturing process of pipe clamps was sheet procurement, dimensions inspection, flame cutting, polishing, press molding, shot blasting, surface painting rolling, etc. Several sections of the pipe clamps, extracted from both the straight and bent sections, were brought for failure investigation, especially the fracture section of the pipe clamps. Tensile test, impact test, hardness test were used for plasticity analysis of different position on the pipe clamp. The chemical composition of the failed clamps was analyzed by ARL4460 direct reading spectrometer. Microstructure and fracture surfaces were examined by scanning electron microscopy (SEM) and optical microscope (OM) to characterize the fracture mechanism. The stress distribution of pipe clamp under the working load was calculated by the finite element analysis software.

3. Results
3.1. Visual inspection
The macroscopic examination of the fracture revealed no obvious plastic deformation appeared at the fracture surface. However, there were some radial steps on the fracture surface and many open cracks along the internal arc surface, which represented brittle fracture characteristics. The crack was perpendicular to the pipe clamp length, and originated from the inner arc surface after the pipe clamp had been pressed and formed. Figure 2 is a macroscopic photograph of fracture cross section, while figure 3(a) shows cracks on the transition from arc to straight segments near the fracture. In figure 3(b), red paint was found in the open cracks, which was located on the inner arc of the pipe clamp. It indicates that cracks were present before the surface was painted.

Figure 1. Fracture location

Figure 2. Fracture surface.
3.2. Chemical analysis
The chemical composition of the failed pipe clamps is shown in Table 1. According to the manufacturing specification, the pipe clamps were made of GB/T 700-2006 grade Q235B steel. Compared with the analysis results, the material met the chemical composition requirements, as specified by GB/T 700-2006.

| Composition | C (%) | Si (%) | Mn (%) | P (%) | S (%) |
|-------------|-------|--------|--------|-------|-------|
| Sample      | ≤0.20 | ≤0.35  | ≤1.40  | ≤0.045| ≤0.045|
| GB/T 700-2006 |       |        |        |       |       |

3.3. Strength properties
Several tensile samples were performed around the fracture and away from the fracture, respectively. Tensile specimens NO.1 and 2 were taken near the fracture location, and specimens NO.3 and 4 were taken far away from the fracture location. The tensile test results were shown in Table 2. It could be seen that the tensile strength (Rm), lower yield strength (Rel), percentage elongation after fracture (A), percentage reduction of area (Z) of the pipe clamps met the requirements of Q235B in GB/T 700-2006.

| NO. | Rel(MPa) | Rm(MPa) | A(%) | Z(%) |
|-----|----------|---------|------|------|
| 1   | 258      | 438     | 35.0 | 66   |
| 2   | 260      | 439     | 35.0 | 63   |
| 3   | 268      | 466     | 35.0 | 63   |
| 4   | 268      | 466     | 34.0 | 66   |
| GB/T 700-2006 | ≥225     | 370-500 | ≥26 | -    |

3.4. Impact test
The impact ductility of the fracture pipe clamps was tested by the Charpy pendulum impact test method. Impact specimens Nos. 1 and 3 were taken near the fracture location, and specimens Nos. 2 and 4 were taken far away from the fracture location. The impact test results were shown in Table 3. It could be seen that the impact energy values of specimen No.1 were 10.6 and 11.1J, which were less than those of specimen No.2, and also lower than the standard requirements. In addition, the experimental results at -10 degrees were much lower than those at room temperature, which indicated that the material had undergone ductile-brittle transition.

According to the Chinese GB/T 17116.1-1997 "Pipe support and hanger", the service temperature of Q235B material is as low as 0 degrees. Through the on-the-spot investigation and data inquiry, the outdoor temperature reached -10℃, when the pipe clamps were fractured. A lower ambient temperature resulted in the reduction of the material plasticity and easy expansion of cracks.
### Table 3. Impact test

| NO. | Experimental temperature (℃) | KV2 (J) |
|-----|------------------------------|---------|
| 1   | 25                           | 10.6    | 11.1   |
| 2   | 25                           | 45.8    | 52.3   |
| 3   | -10                          | 6.8     | 6.2    |
| 4   | -10                          | 7.8     | 8.6    |

GB/T 700-2006

3.5. Hardness test

According to the Chinese standard GB/T 4340.1-2009, Vickers hardness tests were performed on the transition area of the pipe clamps from arc to straight. The test positions are shown in figure 4 and the test results are listed in table 4. The results revealed that the hardness of the inner arc surface of the pipe clamp was much higher than that of other locations. According to the molding process of pipe clamp, the deformation of the transition area between the circular arc and the straight section was the largest, especially on the inner arc surface. The deformation process resulted in a significant hardness increase on the inner arc surface.

### Table 4. Hardness test (GB/T 4340.1-2009)

| Test location | HV1 |
|---------------|-----|
| A             | 272 | 319 | 326 |
| B             | 185 | 199 | 198 |
| C             | 172 | 171 | 168 |
| D             | 150 | 148 | 149 |

![Figure 4. Hardness test positions](image)

3.6. Microstructure analysis

The microfracture analysis showed that both the metallographic structures of the core and the outer arc surface of the pipe clamp transition section were ferrite and pearlite, as shown in figure 5. The grain size was fine and no other obvious organizational defects were observed (figure 5(a) and 5(b)). The grains on the inner arc surface had been deformed, and the deformation ratio was more than 90%. Moreover, the deformation direction of the grain was consistent with the bending deformation direction because of the press molding process, and the thickness of the deformation layer was about 0.3mm (figure 5(c)). The existence of the deformation texture could lead to an increasing hardness and decreasing impact toughness [4].
Cracks originated from the surface of the inner arc fractured through transgranular extension, and expanded inside the pipe clamp. The angle between the crack propagation path and the surface was about 45 degree. Figure 5 (d) was longitudinal section metallographic drawings near the pipe clamp elbow.

![Figure 5. Metallurgical structure and crack morphology](image)

Scanning electron microscopy image of pipe clamp fractures is shown in figure 6. It can be seen that the microscopic features of the crack source location were fan-shaped river patterns and river-like patterns, indicating that the fracture at the internal arc surface was a brittle fracture, the material at the fracture was obviously brittle, and the crack propagation rate was extremely high [5].

![Figure 6. Fracture morphology](image)

3.7. Finite element analysis
In order to analyze the stress distribution of pipe clamp under working load, the overall structural analysis model of pipe clamp and pipe was established as shown in figure 7 using the ANSYS
commercial package. The dimensions of the pipe were as follows: the external diameter of 1020 mm and wall thickness of 11 mm. The dimensions of the pipe clamps were: a width of 144 mm, wall thickness of 18 mm, chamfer radius of 72 mm, and an 80 mm distance between the center of bolt hole and the upper end of clamp. Mechanical properties data of materials in Section 3.3 were used for this simulation.

![Figure 7. The overall structure analysis model](image)

The stress distribution diagram of pipe clamp under working load is shown in figure 8. According to the results, there was a significant stress concentration area at the inner arc of the pipe clamp. The maximum von Mises stress at the middle position of the inner arc surface of the upper elbow could reach 88.45 MPa, which is the zone, where the fracture was initiated.

![Figure 8. Stress distribution of the fracture pipe clamp](image)

4. Discussion
According to the experimental results, the material met the chemical composition and strength properties requirements specified by GB/T 700-2006, but not met the requirements of the results of hardness test, impact test, metallographic analysis and scanning electron microscopic analysis. The fracture of the pipe clamp was a brittle fracture under low stress. The crack originated from the inner curved surface after cold bending, and expanded along the angle of 45 degree toward the elbow of the pipe clamp.

The formation of inner arc surface cracks related to the forming process of the component. During the bending process, the pressure and transverse shear force perpendicular to the surface of the roller were received in the curve of the transition section of the pipe clamps, and the macro deformation occurred under the joint action of the two forces. The microscopic grain of the force was slipping along the crystal surface, and the angle between the slip surfaces to the main deformation direction was approximately 45 degree. The internal arc surface possessed serious deformation, forming the extrusion texture, which caused the surface hardness to become larger and the impact toughness decrease [6]. Therefore, the decrease of the plasticity resulted in the crack finally produced.

In addition, environmental factors were also one of the reasons for the failure of these pipe clamps. The lower temperature of the environment led to a sharp drop in the impact toughness of the material.
[7]. When the service temperature of the material reached -10 ℃, the toughness dropped sharply. Through finite element analysis, the transition between the circular arc and the straight section was the most concentrated area of the entire pipe clamp. The forming defect and the low ambient temperature led to the rapid propagation of the open crack and the eventual breakage in the stress concentration zone.

5. Conclusions and recommendations

The failure analysis revealed that the pipe clamps failed via a brittle fracture under low stress due to a combination of improper control of forming process and low ambient temperature. The deformation of transition zone between the circular arc and the straight section was too large, and it was easy to form an open defect if the process was not properly controlled. In order to avoid this problem, the bending pipe technology parameters could be changed to ensure that the bending pipe deformation did not be excessive. After the molding process, the surface of the large deformation area of the pipe clamp was inspected nondestructively, such as magnetic particle testing (MT) and penetration test (PT). In addition, according to the service environment, the appropriate selection of materials and design parameters is also critical.

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