

Fracture failure analysis of safety valve spring in nuclear power plant

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Abstract: In response to solve the problem of a fractured spring in a safety valve of a nuclear power plant, a series of experiments were carried out, such as macroscopic inspection, chemical composition analysis, mechanical property test, metallographic examination, microscopic analysis and energy spectrum analysis, etc. The results show that the main cause of spring fracture is that the spring is in a corrosive environment with high material strength and hardness, which is sensitive to hydrogen. Eventually, environmental hydrogen embrittlement fracture occurs at the pitting corrosion site.

1. Introduction

As the pressure control unit of various systems in nuclear power plants, safety valves play a crucial role in the safety of nuclear power units. The spring inside the valve pre-set the system pressure by applying spring force to the valve flap, which is indispensable for the functional integrity of the valve. Therefore, improving the reliability of the spring will greatly ensure the stable operation of the safety valve. The causes of valve spring failure are usually stress corrosion, hydrogen embrittlement, etc.,^{[1]-[6]} and rare examples of spring fracture caused by environmental hydrogen embrittlement. This article discusses the causes of the failure of safety valve springs in a certain power plant caused by environmental hydrogen embrittlement, providing a new approach for preventing safety valve spring failure in power plants.

55CrMn, as a commonly used material for springs, has excellent hardenability and mechanical properties but poor corrosion resistance. The spring of a vertical safety valve in a nuclear power plant was found to have broken after being used for about 1.5 years. The spring material is 55CrMn, and the wire diameter is 8 mm. This article conducts various physical and chemical inspections on broken springs, analyzes the causes of spring failure, and provides treatment suggestions.

2. Experiment and result

2.1. Fracture macrostructure inspection

Figures 1-3 shows the macrostructure of the fractured spring. The spring shows varying degrees of corrosion marks on its surface, with localized pitting pits visible. The fracture is located in the fourth circle on the upper side of the installation, and the fractured surface is roughly divided into three areas. The upper and lower sides shown in the photo show corrosion marks, and a metallic luster can be seen in the middle area. The overall fracture is relatively flat, without obvious plastic deformation characteristics. In the middle area of the fracture, radiating edges and crystalline particles can be seen. The radiating edges converge at the lower side of the photo, indicating that the fracture starts from the



lower side of the photo and extends to the upper end. There are visible pitting marks in the initiation zone.



Figure 1. Macroscopic appearance of the fractured spring.



Figure 2. The fracture failure surface of the spring.



Figure 3. The localized surface of the fractured spring.

2.2. Chemical composition analysis

Table 1 shows the analysis results of the chemical composition of samples of fractured springs. The chemical composition of the samples meets the requirements of the standard for the composition of 55CrMn steel, and no hydrogen element was detected in the experiment.

Table 1. Chemical composition analysis results(wt.%).

	C	Si	Mn	P	S	Cr	Ni	H
Sample 1	0.54	0.22	0.80	0.015	< 0.010	0.93	0.06	0 ppm
Sample 2	0.54	0.23	0.81	0.015	<0.010	0.94	0.06	0 ppm
Standard	0.52~0.60	0.17~0.37	0.65~0.95	≤ 0.025	≤ 0.020	0.55~0.95	≤ 0.35	/

2.3. Metallographic examination

Figures 4-10 are the metallographic photo of the sample taken at the longitudinal section of the fracture and near the fracture. Figure 8 is the metallographic photo of the sample taken at the cross-section of the spring. The results show that: 1) the microstructure of the spring is tempered troostite; 2) corrosion and pitting marks can be seen in the cross-section and vicinity of the fracture, with extended cracks visible in the pitting pits, and secondary intergranular cracks and dendritic cracks visible in

local areas of the fracture; 3) no obvious decarburization marks are found on the surface of the spring; 4) The non-metallic inclusion rating of the spring is DT1.0DH0.5.

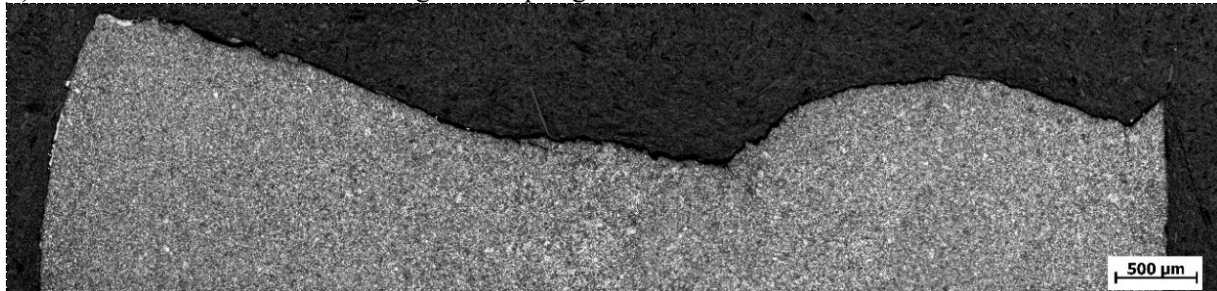


Figure 4. The longitudinal section of the fracture.

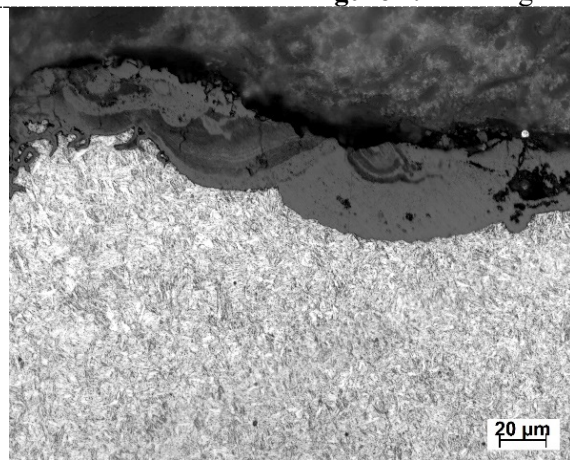


Figure 5. The localized longitudinal section of the fracture at area 1.

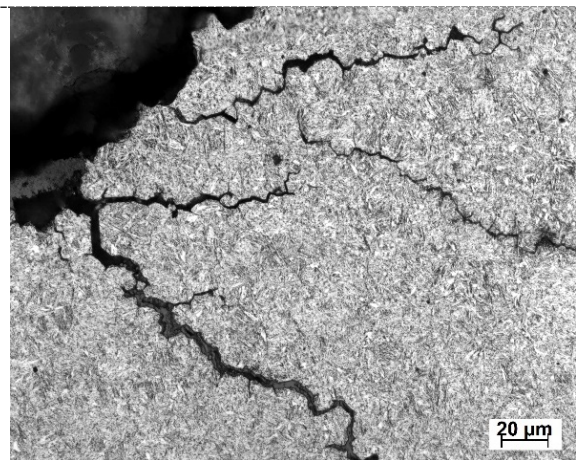


Figure 6. The localized longitudinal section of the fracture at area 2.

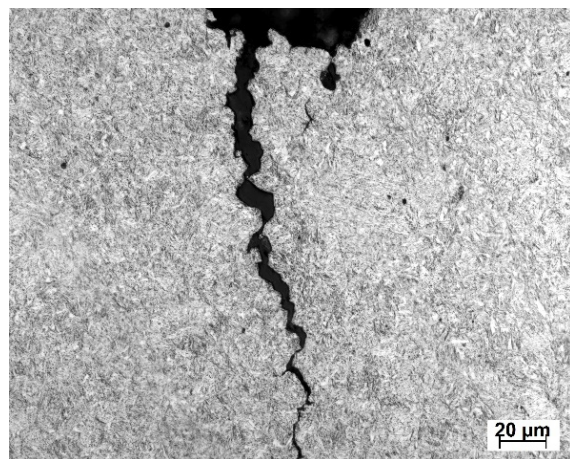


Figure 7. The localized longitudinal section of the fracture at area 3.

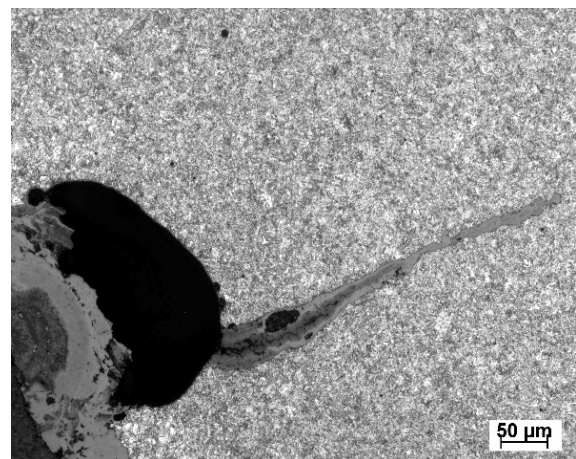
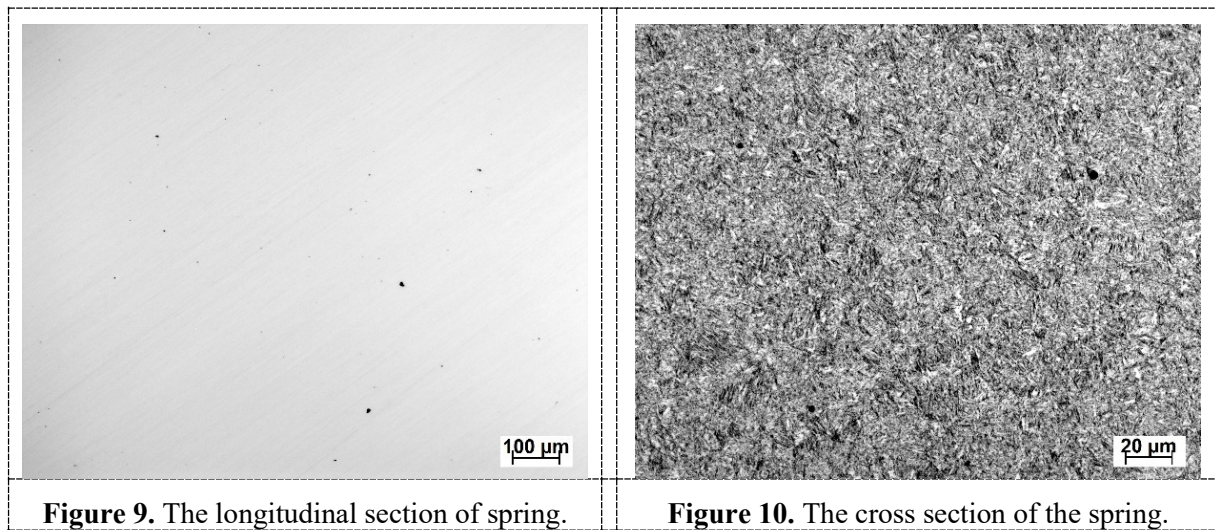
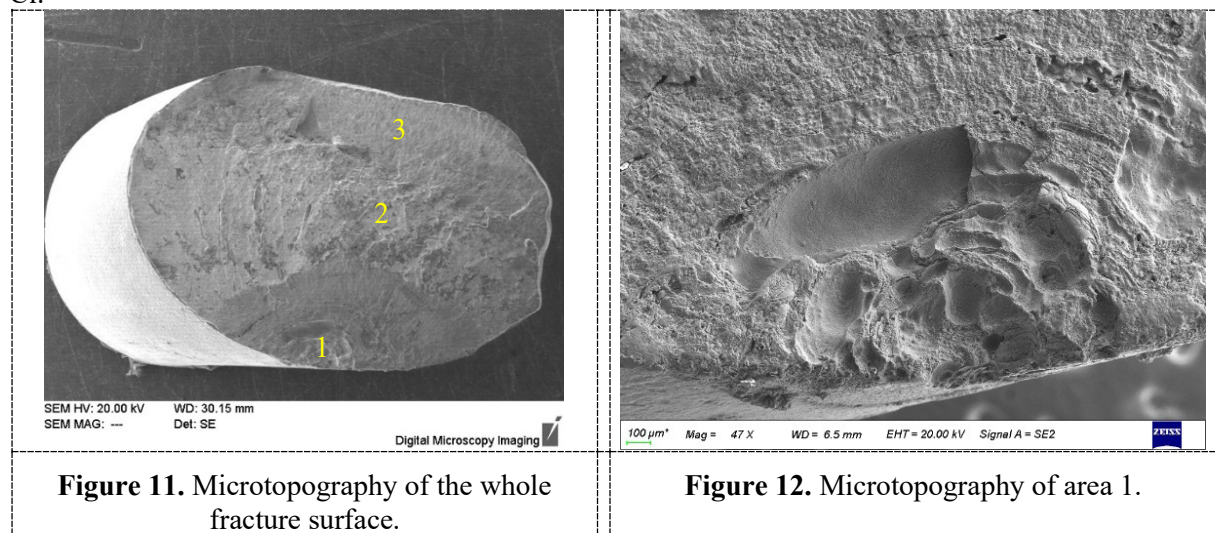


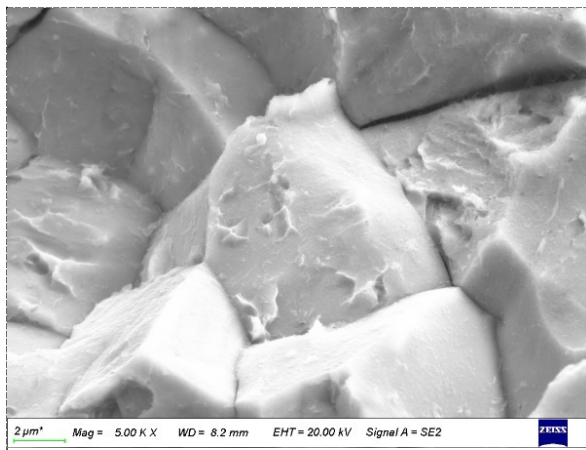
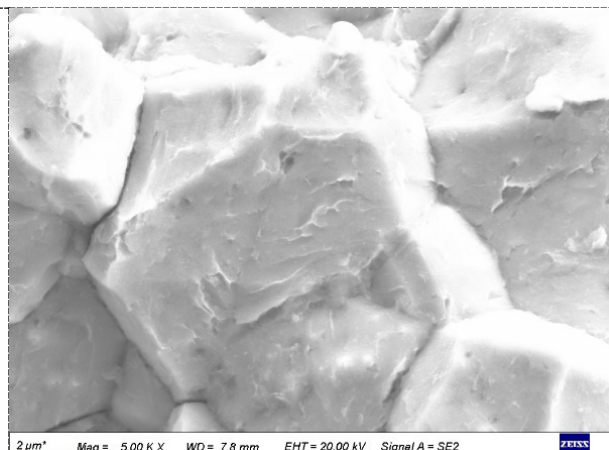
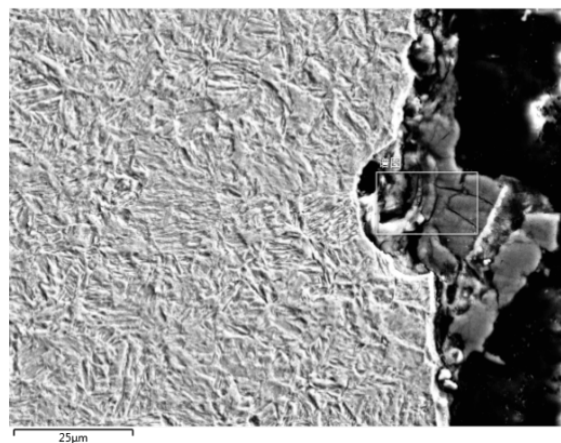
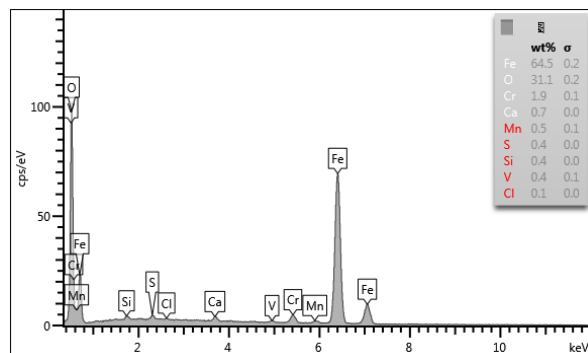
Figure 8. The longitudinal section of the spring near the fracture.



2.4. Fracture microscopic analysis

Figures 11-16 are the photos of the microscopic morphology of the fracture of the spring under the scanning electron microscope. The fracture starts from the lower side, as shown in the photo, and extends to the upper end. Pitting pits and corrosion marks can be seen in the initiation zone, while the uncorroded area presents an intergranular morphology. The extended and final fracture zones are mainly characterized by a rock-sugar-like intergranular morphology, with chicken claw patterns visible locally. At the same time, energy spectrum analysis was conducted on the pitting pits near the fracture section, indicating that the pits contain a certain amount of corrosive elements such as S and Cl.



**Figure 13.** Microtopography of area 2.**Figure 14.** Microtopography of area 3.**Figure 15.** The EDS area of the fractured spring.**Figure 16.** The EDS result of the chosen area.

2.5. Mechanical property test

Table 2 shows the results of the hardness test of the spring samples. Table 3 shows the room temperature tensile strength test results, which is the selection of non-standard specimens with a diameter of 3 mm. The test results show that the Rockwell hardness of the spring sample is about 49HRC, and the room temperature tensile strength is about 1738 MPa. The room temperature tensile strength meets the requirements of GB/T 1222-2016 for the 55CrMn grade but exceeds the lower limit of the standard by about 42%.

Table 2. Hardness test results.

Type		Results		Average
Sample J	HRC	49.0	49.5	49.0

Table 3. Room temperature tensile test results.

R_m (MPa)		
Sample L	1705	1772
≥ 1225		
Standard	The test value exceeds the standard lower limit by approximately 42%.	

3. Discussion

The chemical composition and tensile strength of the spring meet the relevant requirements of GB/T 1222-2016 for the 55CrMn grade, which can exclude the possibility of using the wrong material. However, the tensile strength is much higher than the lower limit of the standard, about 42% higher than the lower limit, indicating high strength and sensitivity to hydrogen. Analysis of the spring fracture surface revealed that corrosion marks were visible on the entire fracture surface at a macroscopic level, with no obvious plastic deformation characteristics. The fracture surface began to crack from the pitting and extended to the opposite side of the final fracture. On a microscopic level, the uncorroded area of the fracture surface exhibits rock-sugar-like intergranular characteristics, with chicken feet visible in local areas, which is a typical hydrogen embrittlement fracture feature. Combined with other physical and chemical inspection results, there are also pitting pits near the fracture surface, and some of the pitting pits show extended cracks. The pitting pits contain a certain amount of corrosive S and Cl elements, and the hydrogen atoms generated by the corrosion reaction will accumulate at the grain boundaries of the material, gradually weakening the intergranular bonding force and making the material brittle. However, no hydrogen element was detected in the near-surface substrate samples of the spring at two locations, indicating that the spring exhibits typical environmental hydrogen embrittlement fracture, where hydrogen embrittlement cracks originate and propagate from pitting pits.

Environmental hydrogen embrittlement is a form of stress corrosion. From an electrochemical perspective, stress corrosion can be divided into two types: one is that the crack tip is located in the anode region, dominated by rapid anodic dissolution, known as stress anodic cracking; the other is that the crack tip is located in the cathode region, dominated by cathodic reactions. The result of cathodic reactions is that a large amount of atomic hydrogen enters the metal interior, producing hydrogen embrittlement, which is called environmental hydrogen embrittlement [7]-[11]. Usually, hydrogen embrittlement and stress corrosion occur simultaneously in the environment, but there are differences in the sensitivity of materials to both. Related studies [12] have shown that austenitic stainless steel is sensitive to Cl⁻ and more prone to stress corrosion due to its crystal structure. For high-strength steel, a hardness higher than 390HV is considered a hydrogen embrittlement-sensitive component. For materials with high strength, hydrogen tends to accumulate in areas where stress is concentrated. Under tensile stress, it accelerates the expansion and concentration along grain boundaries, reduces the bonding force between grain boundaries, and is more likely to lose its ductility, leading to a decrease in strength and an increase in brittleness. The strength of the submitted spring is relatively high, with a Rockwell hardness of 49HRC, which is equivalent to a Vickers hardness of about 500HV. It belongs to the hydrogen embrittlement-sensitive material, and the microstructure is tempered martensite, with low sensitivity to Cl⁻. Therefore, the fracture is mainly dominated by environmental hydrogen embrittlement.

4. Conclusion

Based on the above inspection results and analysis, the main reason for the fracture of the safety valve spring is that the surface of the spring undergoes pitting corrosion under the action of corrosive media, and the spring has high strength and is sensitive to hydrogen. Hydrogen embrittlement cracks initiate at the pitting pits and eventually propagate to fracture.

Based on the above conclusions, it is recommended to: 1) improve the environment in which the spring is located, reduce or avoid the presence of corrosive elements; 2) consider the possibility of improving the corrosion resistance and hydrogen embrittlement performance of springs from the perspective of design material selection, such as using Inconel 718 as the material to manufacture springs. At the same time, the industry can pay attention to the technical standards for spring products, set strength limits, and reduce the hydrogen sensitivity of spring materials from a regulatory perspective.

References

- [1] Goritskii, V.M., Deren, G.S. & Khromov, D.P. An analysis of the causes of failure of safety valve springs. *Chem Petrol Eng* 30, 187–190 (1994).
- [2] Zhiqin Yang. Fracture failure analysis of 50CrVA spring steel[J]. *China Foundry Machinery & Technology*, 2023, 58(3): 83-88.
- [3] Tavares S S M, Pardal J M, Menezes L, et al. Failure analysis of PSV springs of 17-4PH stainless steel[J]. *Engineering Failure Analysis*, 2009, 16(5): 1757-1764.
- [4] Biava M, Brandolin G, Mota N. Spring Failure at North Sea Valve (NSV)[C]//AMPP CORROSION. AMPP, 2023: AMPP-2023-19367.
- [5] He J Z, Lu J N, Deng X Y, et al. Premature fracture of high-strength suspension springs caused by corrosion fatigue cracking[J]. *Results in Engineering*, 2022, 16: 100749.
- [6] Jalali A, Delouei A A. Failure analysis in a steam turbine stop valve of a thermal power plant[J]. *Engineering Failure Analysis*, 2019, 105: 1131-1140.
- [7] Symons D M. A comparison of internal hydrogen embrittlement and hydrogen environment embrittlement of X-750[J]. *Engineering Fracture Mechanics*, 2001, 68(6): 751-771.
- [8] Michler T, San Marchi C, Naumann J, et al. Hydrogen environment embrittlement of stable austenitic steels[J]. *International journal of hydrogen energy*, 2012, 37(21): 16231-16246.
- [9] Zhou C, Song Y, Shi Q, et al. Effect of pre-strain on hydrogen embrittlement of metastable austenitic stainless steel under different hydrogen conditions[J]. *International journal of hydrogen energy*, 2019, 44(47): 26036-26048.
- [10] Huang S, Hui H. Predictive environmental hydrogen embrittlement on fracture toughness of commercial ferritic steels with hydrogen-modified fracture strain model[J]. *International Journal of Hydrogen Energy*, 2022, 47(19): 10777-10787.
- [11] Hussain M, Zhang T, Chaudhry M, et al. Review of prediction of stress corrosion cracking in gas pipelines using machine learning[J]. *Machines*, 2024, 12(1): 42.
- [12] Brahim S V, Yue S, Sriraman K R. Alloy and composition dependence of hydrogen embrittlement susceptibility in high-strength steel fasteners[J]. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 2017, 375(2098): 20160407.

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