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Non destructive testing method research on cracking tendency of welding gas valve surface

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Li Liting, National Key Laboratory of Marine Engine Science and Technology

ABSTRACT

As the engine develops towards low-carbon and zero carbon direction, the thermal and mechanical loads borne by the valve are also increasing, and the lubrication conditions are becoming more severe, leading to intensified wear on its conical surface. Conical welding of hard alloy is an effective way to improve its wear resistance, but after welding, the conical surface of the gas valve is prone to cracking, seriously affecting the reliability of the engine. There is currently no consensus in the industry on which method can effectively characterize the cracking tendency of finished parts. This article uses XRD stress method, ultrasonic testing method, and thermal shocking method to characterize the cracking tendency of different batches of welding gas valves. The difference between the characterization results and the actual machine verification results is compared, and the conclusion is as follows: XRD stress method can qualitatively distinguish the surface stress properties of the welding layer, but it is greatly affected by the measurement position of the components and their own differences, and the differentiation accuracy is limited; The ultrasonic testing method can accurately detect defects at the fusion interface of the weld overlay, but there is no accurate correspondence between the weld overlay defects and the cracking tendency; thermal shocking test can better evaluate the tendency of cracking, and it has no effect on hardness and phase at a temperature difference of 300 â„ƒ.

1 INTRODUCTION

Four-stroke large-bore diesel engines are widely used in marine main engines, auxiliary engines and shore power plants. The wear resistance of the sealing cone surfaces of the intake and exhaust valves, which are important parts of the combustion chamber, directly affects the combustion performance and maintenance cycle of the diesel engine. In recent years, diesel engines have been continuously developed towards high speed and heavy load, and the thermal and mechanical loads on the valves have become larger and larger, resulting in increased wear[1].

To mitigate valve wear and extend service life， researchers and engineers have conducted a large number of studies from different perspectives. Among many wear suppression measures, welding wear-resistant hard alloys on the valve sealing cone surface has been proven to be an effective means. The SAE standard lists typical sealing surface welding alloy types, such as Eatonite alloy, Stellite alloy and Tribaloy alloy[2]. At present, welded valves have been widely used in many high-performance diesel engines. However, due to issues such as inconsistencies in the welding and cone surface machining processes, the common failure form of the valve welding layer is cracking and falling off. This compromises the structural integrity of the valve, resulting in an uneven surface that disrupts effective sealing with the valve seat, ultimately leading to combustion chamber sealing failure. In severe cases, valve fragments are blown into the exhaust pipe system by the combustion gas, causing the turbocharger blades to be damaged. This cracking problem is also the primary technical risk point for diesel engine design institutions when applying welded valves.

The cracking position and typical fracture morphology of the valve welding layer are shown in Figure 1. The crack originates from the sealing cone surface and extends downward from the self-sealing surface and radially inward along the valve disc.

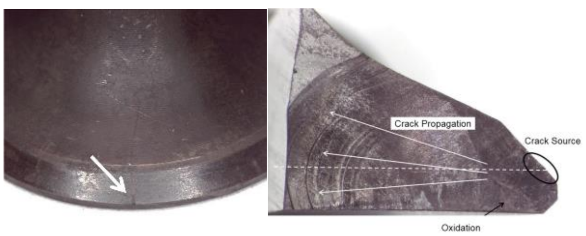

Figure 1 Crack location and typical macroscopic fracture morphology of the surfacing layer[3]

Researchers have conducted a large number of studies on the causes of cracking of the hard alloy welding layer of the valve. For example, D. Morehouse et al. used X-ray diffraction (XRD) to analyze the stress nature of the valve cone surface of the steep compressive to tensile stress gradient in the valves would significantly influence crack initiation and growth[4]. Xue et al. used microscopic observation to find that the fatigue crack originated from the microscopic holes in the welding layer and believed that the non-standard welding process resulting in excessive holes in the welding layer is the core cause of inducing cracking[5]. Zhang of Jiangsu University used simulation analysis to believe that the mismatch of the thermal expansion coefficients between the welding material and the substrate is likely to cause cracking under the alternating thermal stress of the combustion chamber[6].

Regarding the impact fatigue behavior of hard alloys, scholars have conducted mechanism studies from the perspective of materials science. Li Huihui et al. through a variety of fatigue tests and microscopic observations, believed that the impact fatigue of hard alloys is the result of the combined action of multiple factors such as impact load, temperature and corrosive media[7]. Zhang Zhongjian et al. through finite element modeling and thermal shock tests, believed that the thermal stress of hard alloys is composed of the stress difference between the surface layer and the core, the thermal expansion difference between the internal phases of the alloy, and the thermal expansion difference between the welding layer and the substrate[8]..

Scholars have studied the causes of cracking of the valve cone welding layer from multiple means and different angles. However, regarding the characterization methods of the cracking tendency of finished valve parts, diesel engine R & D institutions and suppliers currently adopt a variety of methods, such as stress detection, defect flaw detection, thermal shock tests, etc. There is no consensus in the industry on which method can effectively characterize the cracking tendency of finished parts and screen out parts with a large cracking tendency to avoid their installation in the engine. There is also no relevant report in the literature.

To address the above problems, this paper used X-ray diffraction stress detection test, ultrasonic flaw detection test and thermal shock test to evaluate and characterize the cracking tendency of different batches of welded valves, compared the differences between the characterization results and the actual machine verification results, and explored the accuracy of each characterization method, providing a technical basis for the quality inspection of key diesel engine parts.

2 EXPERIMENTAL MATERIALS

Two different batches of valves from the same manufacturer and with the same part scheme were selected for the study. The sealing surfaces of the valves underwent multiple processes such as welding, rolling, heat treatment and precision grinding. Both batches of valves had been actually operated on a high-power marine diesel engine, and their cracking tendencies are shown in Table 1. Batch A had a high cracking tendency, and cracking was found after a minimum of 227 hours of operation; Batch B had a low cracking tendency, and no cracking was found after more than 8000 hours of operation.

Table 1. Batch number and cracking tendency

Batch	Result	Cracking Tendency
A	Cracking occurred after a minimum of 227 hours of operation	High
B	No cracking after more than 8000 hours of operation	Low

The valve sealing cone surface was welded with Stellite hard alloy. It is a Co-based alloy with a certain amount of alloying elements such as W, Ni, Cr and Mo added. The typical optical microscope (OM) metallographic structure of the Stellite alloy welding layer is shown in Figure 2. Its structure mainly consists of a γ-Co matrix (gray) and dendritic hard carbides of Co, Cr and W (white). The dendrites grow perpendicular to the welding fusion zone and are the typical normal structure of Stellite alloy[9].

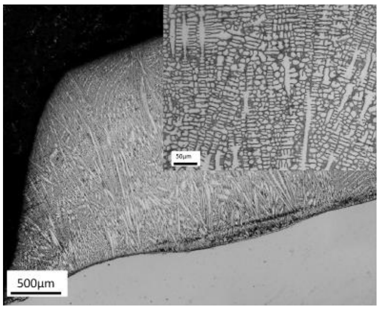

Figure 2. OM metallography of Stellite alloy welding layer

3 XRD STRESS DETECTION TEST

3.1 Equipment and Method

XRD is a typical method for measuring residual stress. The basic principle of measurement is that when there is residual stress in the sample, the interplanar spacing will change. When Bragg diffraction occurs, the diffraction peak will also shift, and the magnitude of the shift is related to the stress magnitude[10].

The Proto-LXRD X-ray stress analyzer was selected as the detection equipment. The measurement parameters were as follows: tube voltage 30 kV, tube current 25 mA, Mn target Kα radiation, collimator diameter 1 mm, Cr filter, (311) diffraction crystal plane, left and right double 512-channel position-sensitive detectors, the corresponding 2θ range was 20°, 17 stations were optimally set within the space ψ angle of ±45°, the ψ swing angle of each station was ±3°, the same tilt diffraction geometry method was used, the diffraction intensity was corrected by LPA, the Pearson function was used for peak determination, the X-ray elastic constants of the material were $S2/2 = 7.18\times10^{-6}$/MPa and $S1 = -1.20\times10^{-6}$/MPa, and the detection was carried out in accordance with ASTM-E915-2010[11], EN15305-2008[12] and GB7704-2017 standards[13].

Three new valves from each of batches A and B were selected for detection. Two sections were measured on the sealing cone surface of each valve, and five points were measured at equal intervals on each section, as shown in Figure 3. To better reflect the stress difference, the ratio of the standard deviation of each measurement value to the average value was used as the variation coefficient for comparison.

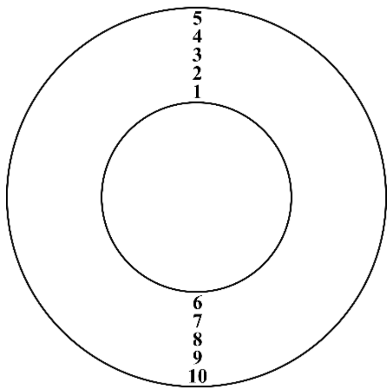

Figure 3. Detection points layout on valve sealing conical surface

3.2 Test Results

The stress detection results are shown in Table 2. It can be seen that the stresses at each point on the cone surface are all negative, that is, compressive stress, and no tensile stress that directly induces radial cracking appears. There are only certain differences in stress amplitudes at each position.

Table 2. XRD measurement results of each part

Batch	A	B

Valve Part Number		062	102	011	001	005	009
Stress /MPa	1	-227.5	-39.5	-171	-253.5	-297.5	-166
	2	-249	-162	-253	-252	-291.5	-143.5
	3	-241.5	-58	-143.5	-138	-190.5	-83
	4	-309	-220.5	-170.5	-315	-223	-195
	5	-261.5	-133	-120	-297.5	-275.5	-217
	6	-196	-91	-62.5	-222.5	-396	-201
	7	-169.5	-179.5	-184	-270.5	-412	-233
	8	-128	-206.5	-137	-119.5	-208	-96.5
	9	-262.5	-278.5	-234.5	-250.5	-225	-193.5
	10	-238.5	-243.5	-394	-149.5	-355	-196

To better reflect the stress difference, the ratio of the standard deviation of each measurement value to the average value was used as the variation coefficient for comparison. The stress variation coefficients of the detected parts are shown in Figure 4.

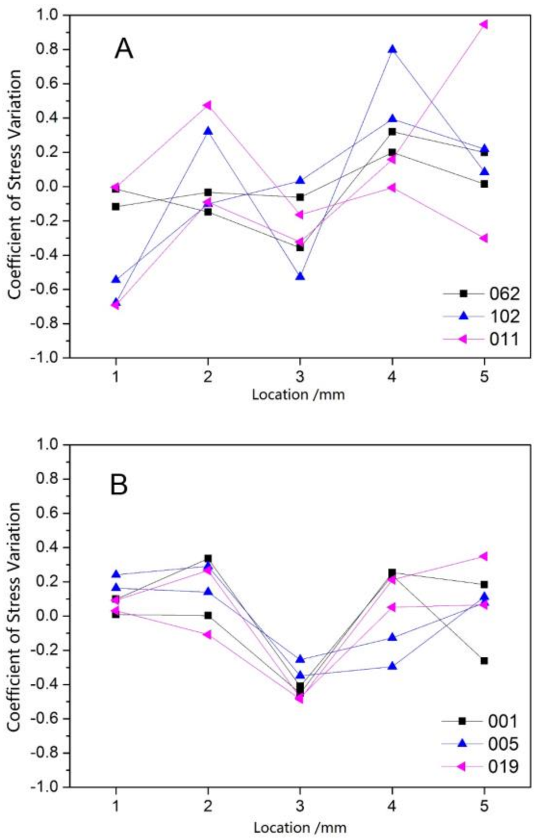

Figure 4. Radial stress variation coefficients of each valve part

It can be seen that for batch A valves with a high cracking tendency, the radial stress difference of a single valve is large, and the stress difference between valves of the same batch is also large. For batch B with a low cracking tendency, the radial stress consistency of a single valve and different parts of the same batch is good.

However, in the rolling process of the selected valves, the rolling head rolls along the inside and outside of the welding layer in turn. Therefore, the stress at the junction of the rolling positions is different, and the radial stress distribution on the sealing surface is M or V-shaped, that is, the radial stress distribution of the part itself has fluctuations, resulting in a low distinguishing accuracy of the above stress consistency.

4 ULTRASONIC DETECTION TEST

4.1 Equipment and Method

At present, traditional contact ultrasonic manual inspection exhibits poor reliability in detecting the internal quality of valve welding layers, while water immersion ultrasonic C-scan detection technology significantly improves defect detection accuracy, making it a more effective solution for characterizing the internal quality of valve welding layers[14]. In the C-scan test, the valve is immersed in water, and the ultrasonic waves are incident from the fire surface of the valve disc. At the same time, the valve rotates axially at a constant speed to scan the entire sealing cone surface. The schematic diagram is shown in Figure 5, and the detection parameters are shown in Table 3.

Table 3. Test parameters of ultrasonic C-scan

Parameters	Value
Probe Frequency	15 MHz
Probe Wafer Size	0.25 inch
Probe Focal Length	1 inch
Water Distance	8 mm
Scan Resolution	0.5 deg
Step Resolution	0.5 mm
Detection Sensitivity	0.4F flat-bottom hole - 40% FSH

Two valves from batch A that had cracked during actual operation and two new unused valves were selected; two valves from batch B that had been in operation for a long time and two new unused valves were selected. A total of 8 valves were subjected to ultrasonic C-scan detection.

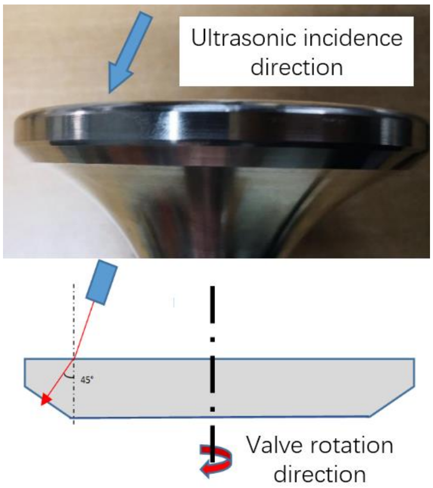

Figure 5. Detection step direction and ultrasonic incidence direction

4.2 Test Results

First, through metallographic dissection, the correspondence between the test results in the ultrasonic C-scan and the actual welding layer defects was confirmed. The ultrasonic C-scan detection result of the cone welding layer of valve A-072 is shown in Figure 6. Red represents the presence of hole defects in the welding fusion zone, and blue represents no defects. It can be seen that only the welding quality at the 2 o'clock position of the valve cone welding layer is good, and there are relatively serious defects at other positions. The radial length of the defects is about 4 mm. After metallographic dissection of this part, it was found that the defect size and position had a good correspondence with the C-scan detection result.

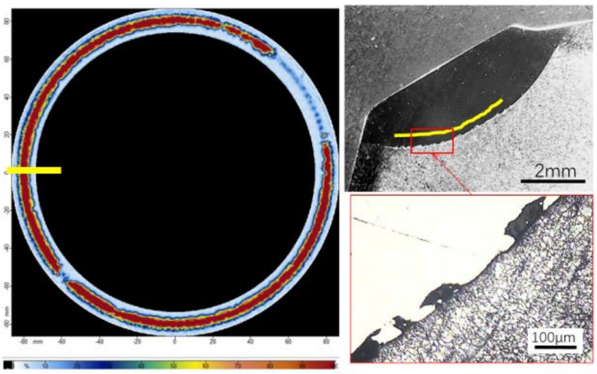

Figure 6. Ultrasonic test defects and metallographic dissection results

The ultrasonic C-scan detection results of each part of batches A and B are shown in Table 4. It can be seen that the total defect area of A-057 is the largest, but the cracking time is shorter than that of A-072. Moreover, the total defect area of B-065 exceeds that of A-072, but no cracking occurred after 8000 hours of operation. That is, except for A-072 - the valve that cracked during actual operation and the ultrasonic C-scan detection result had a good correspondence, the detection results of the other valves did not form a good correspondence with the cracking tendency.

Table 5. Comparison between the results of ultrasonic C-scan detection and the actual machine operation conditions

Batch	Part	Defect Total Area /mm^2	Machine operation time and conditions
A	057	1060.75	After 558h crack
	072	263.40	After 227h crack
	119	0	Brand new and unused
	113	188.75	Brand new and unused
B	065	337.50	No cracks after running for more than 8000h
	042	94	Brand new and unused
	002	0	Brand new and unused
	015	0	No cracks after running for more than 8000h

The reason may be that although the presence of defects in the fusion zone can reflect the welding quality of the alloy layer to a certain extent, the defect holes are not the fundamental cause of the radial cracking of the welding layer.

Therefore, there is no accurate correspondence between the welding defects and the cracking tendency.

5 THERMAL SHOCK TEST

5.1 Theoretical Basis of Methods

The thermal shock test[15] is to heat the test object to a target temperature, keep it warm for a period of time, and then quickly place it in water or other media for rapid cooling to observe the surface state of the test object. The thermal shock resistance of a material refers to the ability of the material to withstand temperature changes and is used to evaluate the performance of the material or part in resisting rapid temperature changes without damage.

The temperature difference that causes crack initiation in the material is defined as the critical temperature difference.[15] Below the critical temperature difference, the alloy will not have crack initiation even after multiple thermal shocks, which means it has no impact on the fatigue performance of the alloy. Therefore, a thermal shock test with a designed critical temperature difference can be used to non-destructively screen parts with welding quality defects.

5.2 Selection of Temperature Difference

Cobalt-based alloys have the following properties[16]: At room temperature, the atomic arrangement of the Co matrix changes from fcc (face-centered cubic) to hcp (hexagonal close-packed) under the action of cyclic loading, resulting in increased brittleness. Therefore, the shielding effect of the Co matrix on the crack tip and the crack tip bridging toughening effect are weakened to varying degrees, and the fatigue sensitivity of the material increases. When the temperature is heated to 300 ℃, as the transformation of the Co matrix from fcc to hcp decreases, the plasticity of the matrix increases, and the oxidation of the material at this temperature is not obvious. Therefore, the shielding effect and bridging toughening effect of the Co matrix are enhanced, and the fatigue sensitivity of the alloy decreases. When the temperature is heated to 500 ℃, the oxidation of the Co matrix along the subcritical cracks is significantly enhanced, resulting in oxygen embrittlement, and the fatigue sensitivity of the alloy increases accordingly. When the temperature is further increased to 700 °C, the fatigue sensitivity of the material decreases due to the brittle-tough transition of the carbide phase.

Therefore, the temperature difference of 300 °C is the lowest point of the phase transformation tendency and oxidation rate of cobalt-based alloys and has the least impact on their properties. Therefore, this temperature difference is selected for the experiment.

5.3 Test Results

A thermal shock test with a temperature difference of 300 ℃ (from 320 ℃ to room temperature) was carried out on the valves of different cracking tendency batches. The heating curve of the test is shown in Figure 7.

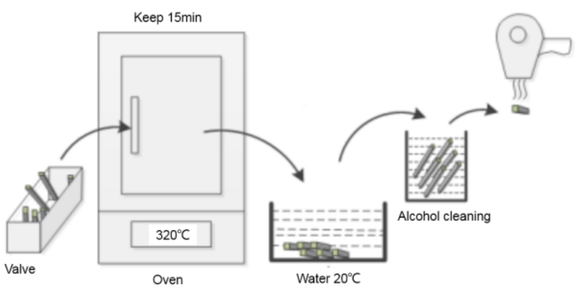

Figure 7. Schematic diagram of thermal shock test process

The test results in Table 6 show that under the thermal shock test with a temperature difference of 300 ℃, the number of cracked valves in batch A is higher, indicating that batch A have a high tendency to crack, which corresponds to the results of the actual engine operation in Table 1. Therefore, the thermal shock test with a temperature difference of 300 ℃ can screen out the valves with a high cracking tendency.

Table 6. Test Results of Thermal Shock Test

Batch	Number of Test Parts	Number of Crack Parts
A	139	26
B	101	3

5.4 Influence of the Thermal Shock on Mechanical Properties

In order to confirm the damage effect of thermal shock test on the air valve, an analysis of the impact frequency on phase and hardness was conducted. The welding layer specimens were subjected to a cyclic thermal shock test with a temperature difference of 300 °C. The XRD phase compositions of the specimens with different cycle numbers were measured respectively (see Figure 8). The results show that the welding layer itself is composed of hcp-Co, fcc-Co, WC, $Cr_{23}C_6$, Cr_7C_3, Co_3W_3C and WC_{1-x}. After up to 50 cycles of thermal shock, its phase composition did not change.

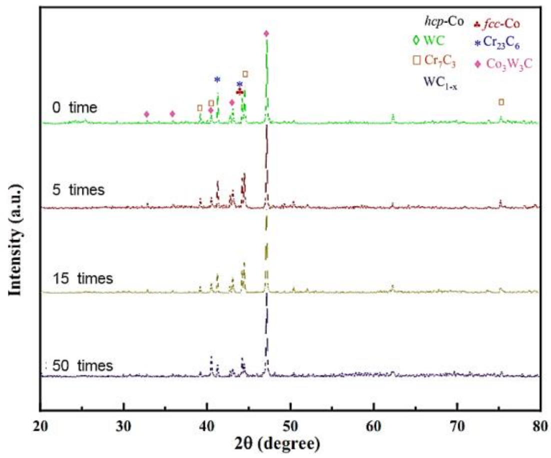

Figure 8. XRD pattern of valve after multiple cycles thermal shock at a temperature difference of 300 ℃

The surface hardness of the welding layer before and after the test was measured and compared (see Figure 9). The results show that after up to 50 cycles of thermal shock, its hardness hardly changed.

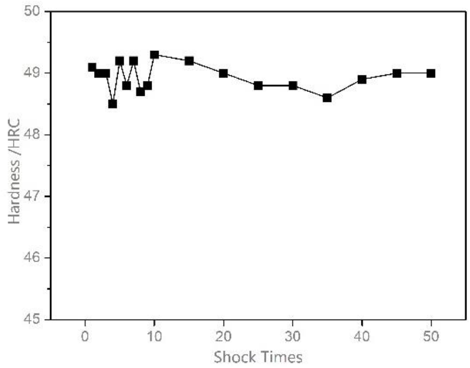

Figure 9. The curve of hardness variation with the number of thermal shocks

6 CONCLUSION

Aiming at the problem that there is no suitable method to characterize the cracking tendency of the diesel engine valve cone welding layer at present, this paper used X-ray diffraction stress detection method, ultrasonic flaw detection method and thermal shock method to evaluate and characterize the cracking tendency of two batches of welded valves respectively. By comparing the differences between the characterization results and the actual machine verification results, the following conclusions were drawn:

1. The XRD stress method can qualitatively distinguish the stress nature of the welding layer surface and can distinguish the cracking tendency of the valve welding layer to a certain extent, but the distinguishing accuracy of the measurement results is limited and is greatly affected by the measurement position of the part and its own differences.

2. The ultrasonic flaw detection method can accurately detect the defects of the welding layer cladding interface and can reflect the cladding quality to a certain extent, but there is no accurate correspondence between the welding defects and the cracking tendency.

3. The thermal shock method can better evaluate the cracking tendency. After XRD testing and hardness testing, it was found that there was no change in phase and hardness after 50 thermal shock tests at a temperature difference of 300 ℃.

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