International Journal of
Automotive Manufacturing and Materials (IJAMM)

Scilight

Article

Failure Analysis of Cracking in a Diesel Engine Aluminum Alloy Cylinder Head

Yaling He *, Zhifang Gu, Guoqiang Yu, Jifeng Deng, and Chaoqun Dai

Dongfeng Automobile Co., Ltd. (DFAC), Wuhan 430000, China
* Correspondence: heyaling@dfac.com
Received: 1 April 2025; Revised: 6 May 2025; Accepted: 30 May 2025; Published: 1 July 2025

Abstract: The failure of cylinder head cracking involves many factors such as engine system, test control, cylinder head casting, heat treatment, raw materials, machining, etc. This article focuses on the abnormal cooling system of a certain diesel engine during the cold and hot shock durability test. Through clear investigation and confirmation, it is found that the cracking occurred inside the cylinder head, and the specific location of the cracking is identified. Through a series of failure analysis and testing, including cylinder head material, performance, macroscopic and optical microscopic examination of the fracture surface, and casting residual stress, the true cause of the cylinder head cracking is analyzed. The main defects are surface defects of the cylinder head casting, including micro-pores and micro-shrinkage porosity. At the same time, casting residual stress and small R-angle at the root of the water jacket are also factors that promote crack formation, and improvement suggestions are proposed.

Keywords: cylinder head; cracking; fracture analysis

1. Introduction

The cylinder head is one of the most complex components in a diesel engine. It not only has to withstand the mechanical loads from the explosive pressure during the combustion process and the pre-tensioning force of the cylinder head bolts, but it also has to endure the thermal loads from the high-temperature and high-pressure gases in the combustion chamber. Under the influence of cooling water, the temperature distribution in different parts of the cylinder head can vary, leading to thermal stress. Additionally, the strength of the aluminum alloy material used for the cylinder head decreases to some extent when exposed to high temperatures, increasing the risk of cracking and failure. Causing cracking at different positions, such as the cylinder head firing surface, injector holes, and preheating plug holes [1–3].

This article investigates the abnormal cooling system of a self-developed light diesel engine during a cold and hot shock durability test. It clearly confirms that the cracking occurred inside the cylinder head, identifies the specific location of the cracking, analyzes the true cause of the cylinder head cracking, and proposes improvement direction suggestions.

2. Test Failure Phenomenon

During a thermal shock durability test, an aluminum alloy cylinder head of a diesel engine exhibited abnormalities in the durability test after running for 260 h. The coolant in the expansion tank was significantly reduced. Upon checking the engine test operation data, no abnormalities were found in the power, torque, exhaust temperature, inlet and outlet water temperatures, and inlet and outlet water pressures. After shutting down, an endoscope was used to inspect the cylinder, revealing a small amount of liquid in the combustion chamber of the fourth cylinder, as shown in Figure 1. No abnormalities were found in the other three cylinders.

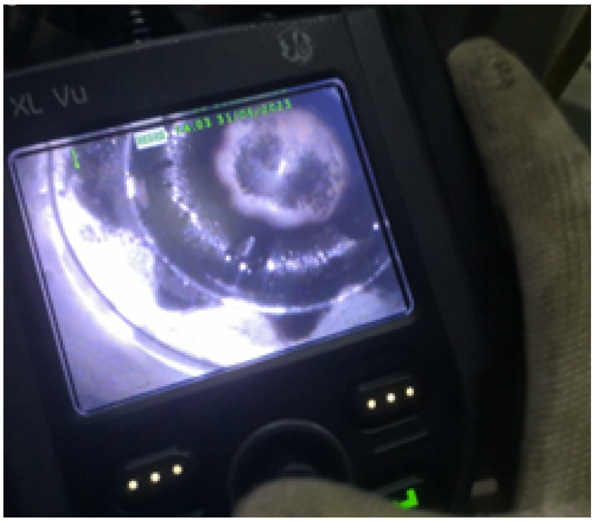

Figure 1. Liquid in the combustion chamber.

3. Problem Investigation

3.1. Analysis of Possible Paths for Water-Gas Intercommunication

Based on the schematic diagram of the engine cooling system and the flow direction of the engine coolant, the coolant enters the cylinder block cooling water jacket through the water pump, passes through the cylinder gasket into the cylinder head cooling water jacket, and then flows out from the thermostat. The EGR cooler draws water from the cylinder block, while the EGR valve draws water from the cylinder head, as shown in Figure 2. The possible paths for coolant entering the combustion chamber are analyzed as follows: (1) Internal water-gas intercommunication in the EGR cooler; (2) Internal water-gas intercommunication in the EGR valve; (3) Seal failure of the GSKT-CH; (4) Internal cracking of the cylinder head; (5) Deformation of the combustion chamber surface of the cylinder block or cylinder head, etc.

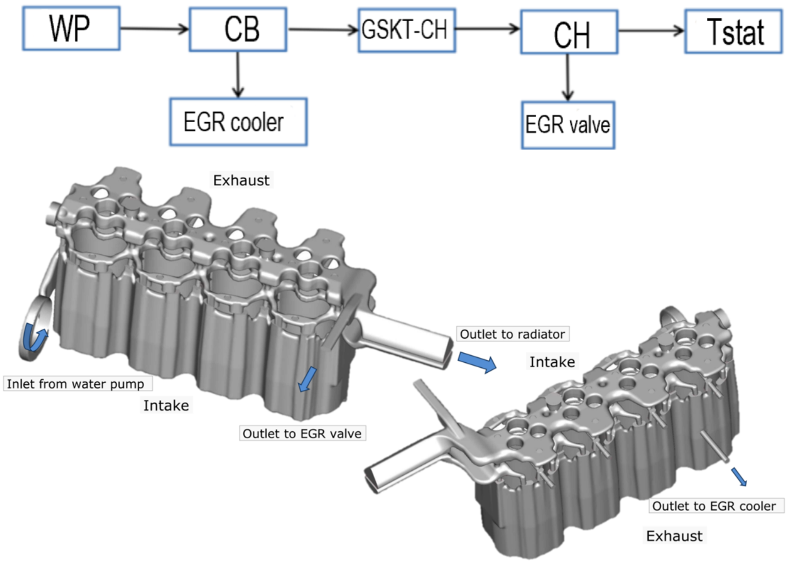

Figure 2. Paths for Coolant Entering.

3.2. Carry Out Fault Diagnosis

After discovering an abnormal decrease in coolant, the engine was shut down for inspection. It was found that there were traces of coolant in the piston combustion chamber. Based on the analysis of the path of water and gas intermixing, the following fault diagnosis was carried out.

Step 1: The EGR valve and EGR cooler were replaced with new parts, and the engine was run for an additional 10 h. An endoscope was inserted through the engine preheating plug hole to observe the interiors of cylinders 1 to 4. It was found that cylinders 1 to 3 showed no abnormalities, but cylinder 4's combustion chamber had wet traces, ruling out internal leakage issues with the EGR valve and EGR cooler.

Step 2: The exhaust gas connection pipe was removed, and the engine was run in reverse drag conditions. Gas was observed exiting from the exhaust manifold gas interface. After stopping the engine, a small amount of coolant was found in the exhaust manifold, focusing the problem on the cylinder block, cylinder gasket, and cylinder head.

Step 3: The engine was removed from the frame for disassembly inspection. Following disassembly protocols, the torque of the cylinder head bolts was first checked, and no abnormalities were found in the torque measurements. Next, a surface pressure test of the cylinder gasket was conducted, and no discontinuities were found in the surface pressure results. Visually, no abnormalities were observed on the cylinder gasket.

Step 4: A dial gauge was used for preliminary testing of the flatness of the combustion chamber surfaces of the cylinder block and cylinder head. The measurement results showed that the flatness of both the cylinder block and cylinder head was within 0.03, initially indicating that the combustion chamber surface of the cylinder head had not deformed. Subsequently, sealing tests were conducted on the water jackets of the cylinder block and cylinder head. The cylinder block passed the sealing test, but the pressure for the cylinder head water jacket sealing test could not be established, as shown in Figure 3, indicating that a crack had developed inside the cylinder head, which was identified as the main cause of the engine's water and gas mixing.

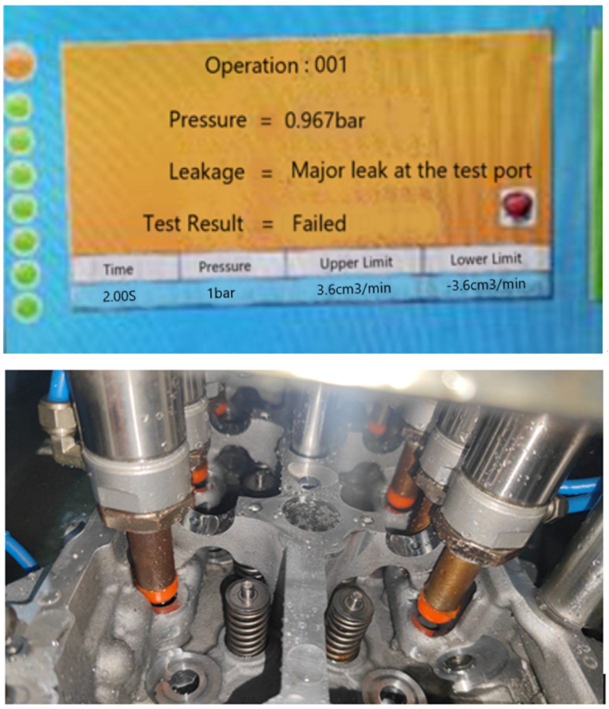

Figure 3. Sealing Test.

4. Analysis of Cylinder Head Crack Detection

4.1. Confirmation of Crack Location

A sealing test was conducted on the water jacket of the cylinder head, sealing the combustion chamber surface and the outlet hole of the thermostat. Air was introduced through the water inlet hole of the EGR valve, with a pressure of 1 bar. According to the standard testing method, it was found that the pressure of 1 bar could not be established, indicating a significant leak. A water test was performed to locate the leak points, and the results showed that numerous bubbles were emerging from the injector holes of cylinders 1 to 4. Specifically, see Figure 2. It is inferred that there are cracks at the injector holes of the cylinder head [4–6].

Based on the structure of the water jacket of the cylinder head, a cross-section was taken 20 mm from the combustion chamber surface, followed by a visual inspection. Cracks were found at the top surface of the water jacket below the injector holes, with cracking occurring at the injector holes of all four cylinders. The specific locations of the cracks are shown in Figure 4.

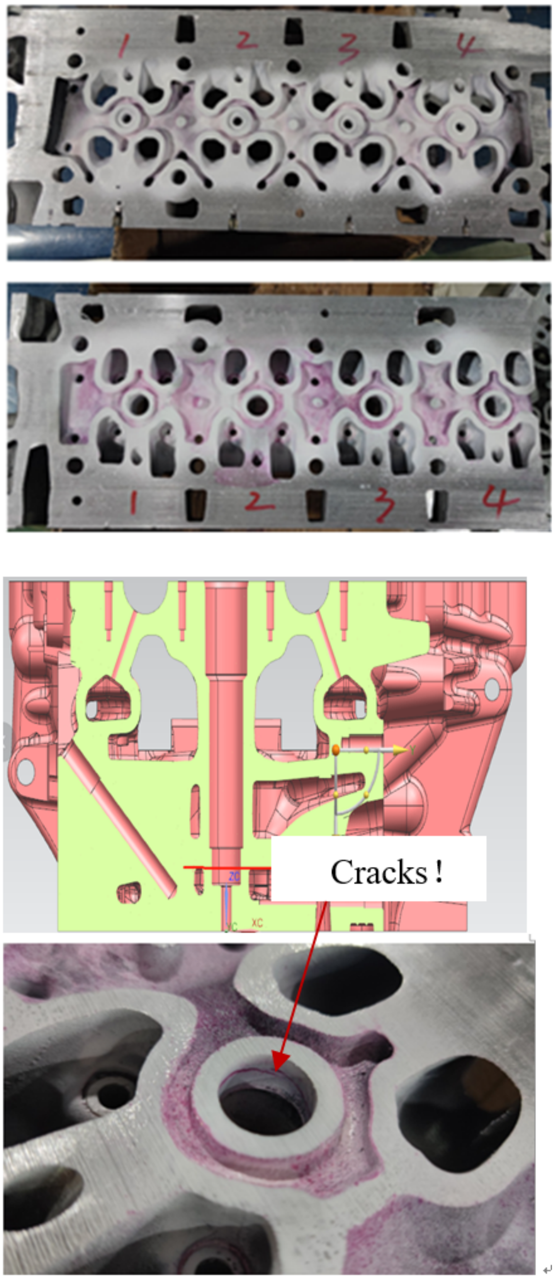

Figure 4. Locations of the Cracks.

4.2. Material and Performance of the Cylinder Head

The cylinder head is made using gravity casting, with the sand core made of coated sand hot core, and subjected to T6 heat treatment [7]. The material composition of the samples from the same batch meets the material standard requirements. The mechanical performance indicators also meet the requirements, with specific test results shown in Figure 5. A detailed flatness measurement was conducted on the combustion chamber surface of the failed cylinder head, and the results indicated that the flatness evaluation at the sealing position of the cylinder head was within 0.03, while the flatness of the entire large surface was also within 0.05. No thermal deformation was observed on the combustion chamber surface of the cylinder head, indicating that there were no abnormal combustion or excessive thermal load during the durability test. Additionally, hardness testing was performed on the combustion chamber surface of the failed part and the cut samples, with hardness values ranging from 100 to 110 HB, which meets the requirements. It is inferred that the mechanical performance of this cylinder head meets the design requirements [8,9].

Hardness: fire face-HB1, top face-HB2			
	HB1	HB2	
Specification	>90HBW	>85HBW	
1	107	98	
2	109	99	
Mechanical characteristics			
	Part		
	Rm>210MPa	Rp0.2>175MPa	A>1%
T1	326	251	4.5
T2	326	255	4.0
T3	330	253	4.0
T4	300	235	3.0

Figure 5. Material Mechanical Performance.

4.3. Macroscopic Examination of the Fracture Surface

The cracked area of the failed cylinder head is not completely separated. A grinding wheel was used to cut the failed cylinder head, exposing the crack at the injector hole of cylinder 4 for sampling. A macroscopic examination of the fracture surface was conducted using the large end of the sample block for analysis, and the fracture surface is shown in Figure 6. The results of the macroscopic examination are as follows:

(1) The fracture surface exhibits a black oxidized color, indicating a brittle fracture;

(2) There are five steps on the fracture surface, with the step fractures being silver-white and unoxidized. The five steps divide the fracture surface into five regions along the circumferential direction. This feature indicates that each region of the entire fracture is formed by the expansion of independent crack sources;

(3) Each region has distinct radial striations, all pointing towards the outer edge of the fracture (i.e., the rounded root), indicating that the rounded root of the outer edge of the fracture is the source of the fracture cracks;

(4) The distribution and orientation characteristics of the cracks are as follows: this structure is subjected to alternating torsional loads. When the two halves of the fracture are combined, two independent cracks are interwoven. The cracks in the entire fracture are arranged in two directions, with three cracks having a right-handed twist and two cracks also having a right-handed twist, but with a very small helical angle. The ends of the cracks in each region are below the step root. Based on these features, a preliminary judgment can be made regarding the crack orientation in each region and the initiation and propagation direction of the entire fracture [10,11].

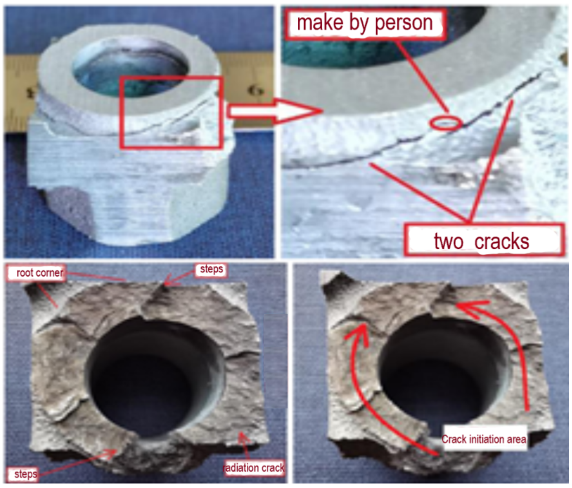

Figure 6. Fracture (Crack) Surface.

4.4. Optical Analysis and Scanning Electron Microscopy of the Fracture Surface

Optical microscopic examination and scanning electron microscopy analysis were performed on five regions labeled 1# – 5# on the fracture surface. A macroscopic examination of the fracture region 1# was conducted using an optical microscope, and the examination area is shown in Figure 7.

A significant number of pores and micro-void defects were found in the corresponding area.

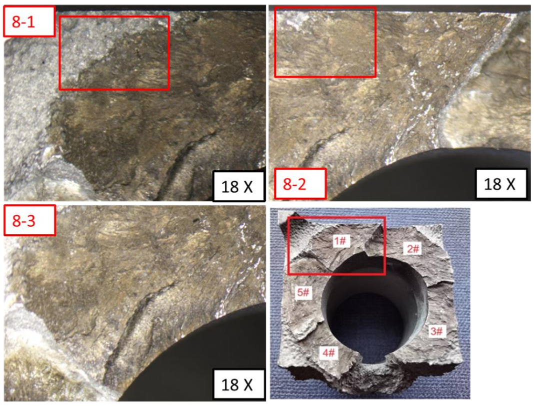

Figure 7. Examination Area.

For the areas marked 8-1 and 8-2 in Figure 7 of Region 1#, electron microscopy scans were conducted, revealing a considerable number of pores and micro-void defects, as shown in the following Figure 8. The area marked 8-1 corresponds to 10-1/2/3/4 in Figure 8, while 8-2 corresponds to 9-1/2/3/4 in Figure 8.

After embedding, grinding, polishing, and etching the fracture surface (with a 20% dilute nitric acid solution), electron microscopy scans were performed to further examine the cross-sectional casting defects and microstructural defects. The results indicated the presence of hydrogen pores on the surface and inside the casting. Through electron microscopy scanning, seven pores and twelve micro-voids were distributed along a 5 mm length interface at the junction of the crack surface and the casting surface. These micro-pores and micro-voids measured approximately 0.1 – 0.4 mm. In the examination of four other areas, a significant number of pores and micro-void defects were also found. Scanning the micro-pores or micro-voids on the fracture surface of the casting revealed that the size of the surface pores or micro-voids could reach up to 0.2 mm. In the examination of Region 5, micro-void defects were found at the crack boundary. The electron microscopy scan at the crack tip indicated the presence of fatigue striations and a large number of river patterns (cleavage steps), with the river patterns being perpendicular to the fatigue striations and pointing in the direction of crack propagation. As shown in Figure 9, this type of fracture indicates that the crack is a result of brittle fatigue fracture, with the source of the crack defect originating from casting defects on the surface of the casting.

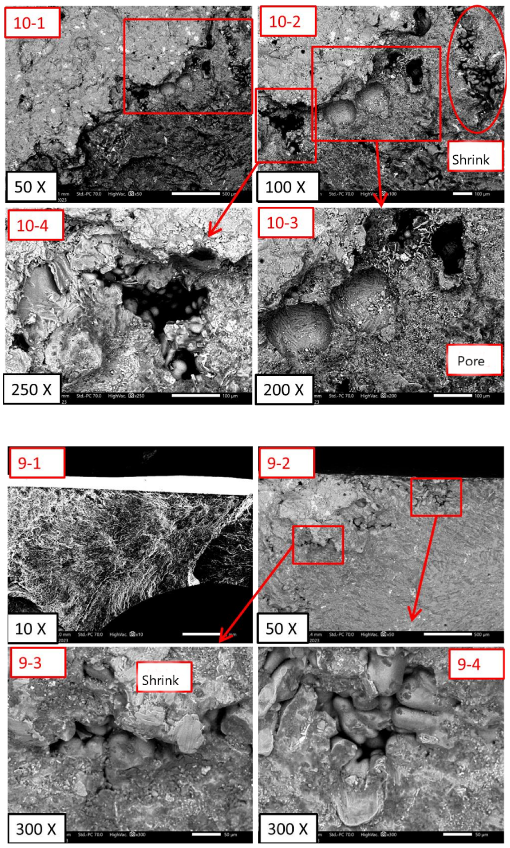

Figure 8. Electron Microscopy Scanning Photos of Fracture Region 1#.

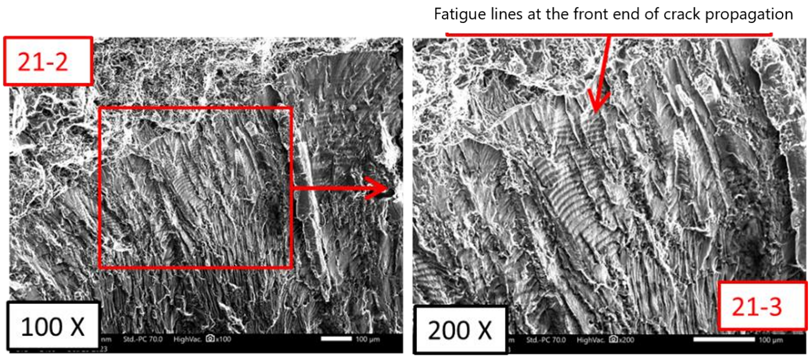

Figure 9. Scanning Electron Microscope (SEM) Images of Fracture in Area 5#.

4.5. Metallographic Structure and Residual Stress Detection

The SEM energy spectrum analysis indicates that the microstructure of the casting consists of a solid solution and eutectic structure, with a small amount of iron-rich phase distributed at the grain boundaries. As shown in Figure 10, the metallographic structure includes: α (Al) dendrites + short rod-like or granular eutectic silicon + a small amount of blocky primary silicon. The microstructure is normal without signs of overheating or overburning.

Residual stress measurements were conducted at points A and B in the water jacket near the injector hole, yielding residual stress values of 63 and 20.8, respectively. The stress is relatively high, which may promote crack formation.

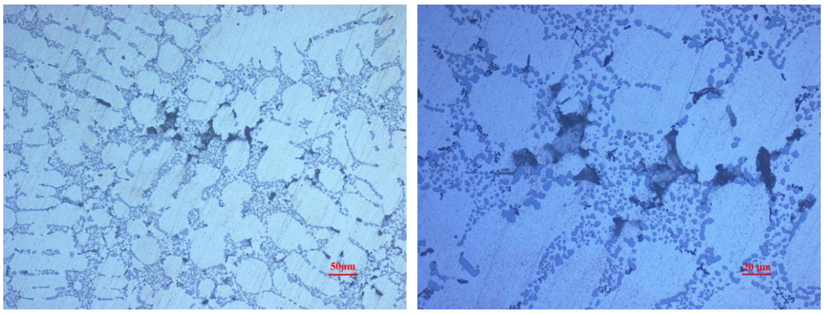

Figure 10. Metallographic Structure (×200 and ×500).

5. Analysis and Discussion of Fracture Detection Results

(1) Location and Distribution of Cracks at the Injector Hole. Cracks at the injector hole are located at the rounded corner rather than at the thinnest section, indicating that there is stress concentration at the rounded corner, which measures approximately 1.5 mm, as shown in Figure 11. Additionally, cracks in the water jacket were found on the intake side near the fire surface of cylinder 4. The water jacket cracks are much finer than those at the injector hole, and no water jacket cracks were present until the cracks at the injector hole had fully developed. It is possible that the cracks at the injector hole fully developed before the water jacket cracks began to form and propagate.

(2) The cracks are brittle fatigue cracks. Scanning at the crack tip shows the presence of fatigue striations and a significant amount of river patterns (cleavage steps). The river patterns are perpendicular to the fatigue striations and point in the direction of crack propagation.

(3) The source of the cracks comes from casting defects on the surface of the castings. There are numerous defects on the casting surface near the crack fracture, mainly including porosity, micro shrinkage, etc. Approximately six hydrogen pore defects, each measuring 0.1–0.2 mm, are distributed over a length of 3 mm in the crack initiation area of the crack defect.

(4) The crack initiation area contains a small amount of brittle fracture dendrites. Additionally, there is evidence of corrosion on the crack surface near the inner hole side of the injector hole.

(5) The metallographic analysis of the casting and the results of electron microscope metallography indicate:

(i) The microstructure of the casting is mainly composed of solid solution (dendrites), eutectic structure, and iron-rich phases between dendrites. No abnormalities were observed in the structure.

(ii) The dendrites are relatively coarse, and the modification treatment needs to be optimized.

A comparison of the metallographic structure of similar areas in similar products is required.

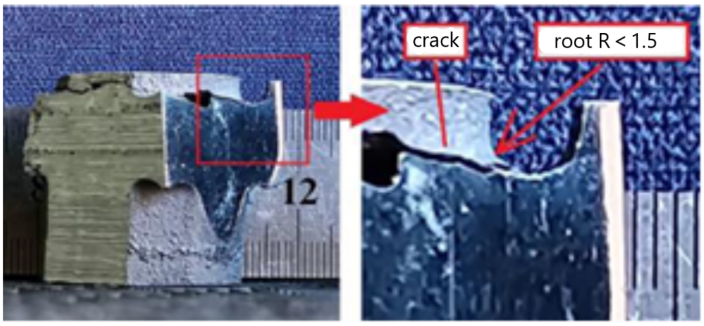

Figure 11. Rounded Corners of Cracked Areas.

6. Conclusions and Recommendations

In summary, the crack failure of the accessory at the injector hole of the cylinder head is attributed to fatigue crack failure under alternating mechanical stress, thermal stress, and a weak corrosive environment [12–15]. The contributing factors are as follows:

(1) The source of the cracks mainly comes from surface defects of the casting, including microscopic porosity and micro-shrinkage.

(i) The porosity (mainly hydrogen porosity) and microscopic shrinkage on the surface of the casting are primarily due to a high hydrogen content in the aluminum melt at the surface, which causes hydrogen to precipitate and form pores during solidification, or hydrogen to accumulate and precipitate around the dendrites, resulting in micro-shrinkage (which should actually be referred to as gas shrinkage).

(ii) The hydrogen content in the surface aluminum melt of the casting mainly has two sources: (a) It is related to the hydrogen content in the melted aluminum, where high moisture content in the raw materials and melting equipment, as well as insufficient degassing and refining, can lead to a higher hydrogen content in the melted aluminum. (b) The high moisture content in the molding materials, such as the core sand, can lead to significant gas generation, causing a reaction between aluminum and water at the mold (core) interface, resulting in hydrogen being generated and dissolved in the surface aluminum melt of the casting.

(2) The microstructure is relatively coarse (especially near the cracks).

(3) Additionally, there may be structural factors in the casting that promote cracking, such as small radii at the fracture site, which lead to greater stress concentration (including thermal and mechanical stress).

(4) The residual stress in castings, especially the residual stress after heat treatment, is worth paying attention to. These residual stresses may also lead to the formation of cracks.

Based on the analysis of the above causes, the directions for improvement of the cylinder head casting are as follows:

(1) Control the core-making process during the casting production, especially controlling the gas generation from the sand core and the moisture content of the sand core. This will reduce the reaction between water vapor in the sand core and the molten metal, thereby decreasing the hydrogen content in the aluminum melt.

(2) Strengthen the degassing and refining of the aluminum melt to reduce the gas content in the aluminum, minimizing the tendency for gas holes and micro-shrinkage on the surface of the casting.

(3) Enhance the modification treatment of the casting to further refine the grain size, improving the toughness and crack resistance of the casting material.

(4) Increase the R corner of the cracking area of the water jacket and optimize the cooling of the bottom mold of the cylinder head to reduce residual stress, among other measures.

Author Contributions: Y. H.: conceptualization, methodology, software; Y. H.: data curation, writing—original draft preparation; Y.H.: visualization, investigation; Y.H.: supervision; Y.H.: software, validation; Y.H.: writing—reviewing and editing. Z. G.: reviewing. G. Y.: reviewing. J. D.: reviewing. C. D.: reviewing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability: Statement: Not applicable.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Reference

1. Chen, H.; Wang, Y. Cracking Analysis of Fuel Injector Holes in Aluminum Cylinder Head of Diesel Engine. *Automot. Parts* **2024**, 71–75. https://doi.org/10.19466/j.cnki.1674-1986.2024.5.016.
2. Luo, J.; Chen, T.; Wen, S.; Gao, W.; Zhong, W. Analysis and Optimization of Cracking on the Thermal Surface of a Certain Engine Cylinder Head. *Small Intern. Combust. Engines Veh. Technol.* **2024**, *53*, 11–13.
3. Zhong, Y.; Song, L.; Yang, M.; Sun, Q.; Guo, Z.; Xiao, X. Analysis of Cracking Failure of Automotive Engine Cylinder Head. *Intern. Combust. Engine Parts* **2023**, 79–81.
4. Luo, C. Analysis and Improvement Plan for Cracks in the 240D Cylinder Head. *Diesel Locomot.* **2009**, 39–41.
5. Zeng, X.; Wang, G.; Liu, Y.; Liu, J.; Feng, Y.; Shi, X.; Lou, D.; Zhang, L.; Wei, T.; Li, Z. Enhancing the Reliability Assessment System for Crucial Powertrain Components through Design, Simulation, and Experiment. *Int. J. Automot. Manuf. Mater.* **2023**, *2*, 4. https://doi.org/10.53941/ijamm.2023.100010.
6. She, L. Analysis and Control of Defects in 4GD1 Aluminum Alloy Cylinder Head Castings. In Proceedings of the 2013 China Foundry Activity Weekly Collection Jinan: Chinese Society of Mechanical Engineering, Jinan, China, 2–5 November 2013; pp. 1–6.
7. Lai, H.; Fan, H. Casting process method for aluminum cylinder head of automobiles. *Chin. Foundry Prep. Technol.* **2003**, 29–31.
8. Liu, G.; Wang, Y.; Xu, S. Research Status of Casting Technology for Aluminum Alloy Cylinder Blocks and Cylinder Heads in Automobiles. *Heilongjiang Sci. Technol. Inf.* **2017**, 18.
9. Jiang, H.; Yang, G.; Zhang, X.; Feng, Q. Analysis of Cracking Causes of Automotive Engine Cylinder Heads. *Phys. Test.* **2015**, *33*, 45–47.
10. Zhong, Q.; Zhao, Z.; Zhang, Z. The Development of Fracture Mechanics and the Study of Microscopic Fracture Mechanisms. *Mech. Strength* **2005**, 358–370.
11. Liu, X. Analysis and Countermeasures of Diesel Engine Cylinder Head Injector Hole Cracking. *Equip. Manuf. Technol.* **2020**, 132–134+152.
12. Chen, J. *Automotive Structure*, 5th ed.; People's Communications Press Society: Beijing, China, 2006.
13. Li, Z. Engine Integrated Exhaust Manifold Cylinder Head Design and Fluid Structure Coupling Heat Transfer Analysis. Master's Thesis, Shenyang University of Technology, Shenyang, China, 2020.
14. Yu, W.; Jiang, L. Application of Carbon Fiber Reinforced Aluminum Matrix Composites in Automotive Industry. *Int. J. Automot. Manuf. Mater.* **2024**, *3*, 3. https://doi.org/10.53941/ijamm.2024.100009.
15. Han, X. Design and optimization of integrated exhaust manifold cylinder head. *Intern. Combust. Engine Power Unit* **2019**, *1*, 52–54.