Chapter

The Position and Function of Macroscopic Analysis in the Failure Analysis of Railway Fasteners

Guodong Cui, Shuaijiang Yan, Chengsong Zhang, Dazhi Chen and Chuan Yang

Abstract

Macroscopic analysis plays an important role in failure analysis, which cannot be replaced by other analyzing methods. In recent years, with the development of characterization techniques, more and more engineers and technicians rely on the advanced analytical testing methods in the process of failure analysis, ignoring the methods and means of macroscopic analysis. This can easily lead to some wrong judgments. Therefore, this chapter will combine with the cases to explain the position and role of macroanalysis in the failure analysis of rail fastening clips and to offer references for engineers and technicians in relevant fields.

Keywords: failure analysis, macroscopic analysis, railway fastener, fracture, crack initiation

1. Introduction

Macroscopic analysis refers to the method of observation, description, and analysis of the macroscopic features, such as shape, morphology, dimensional accuracy, cracks, processing defects, fracture surface, etc., of materials by the naked eye or using a magnifier at a low magnification (usually less than 50 times magnifying) [1–3]. Due to its simplicity and convenience, macroscopic analysis is widely used in the production and engineering practice. However, in recent years, with the development of the material characterization techniques and equipment, more and more engineers and technicians are inclined to rely on the advanced characterization equipment in the actual analysis and testing process, thus ignoring various macroscopic analysis methods. Particularly in the failure analysis of actual working parts, if due attention failed to be paid to macroanalysis, some wrong judgments can be easily made, which will eventually lead to the catastrophic consequences [4, 5].

In the process of failure analysis, macroanalysis is usually the first and the most important step. Through the macroanalysis, the failure mode, such as wear, corrosion, severe plastic deformation or fracture, etc., can be determined rapidly. In addition, the specific location of the failing point in the entire component can be determined by macroanalysis, such as whether the failed position bear the maximum force, whether the stress is concentrated at specific locations, and whether a processing defect exists near the fracture surface, etc. These judgments are helpful to find the specific cause of the failure.

The application of macroscopic analysis in metal materials mainly consists of etching, imprinting, nondestructive testing, and fracture surface observation methods [6]. Among them, the etching and imprinting methods are mainly used for detecting metallurgical defects such as microstructural segregation, inclusion, looseness, and pores in metal parts and are also used for cleaning the fracture surface of the failed samples [7, 8]. However, with the continuous improvement of manufacturing processes and technologies in recent years, the metallurgical defects in metal parts have been greatly reduced, and the failure of metal parts is rarely caused by metallurgical defects. Therefore, the application of etching and imprinting methods in failure analysis became fewer. Comparing to the etching and imprinting methods, nondestructive testing technique is an important means for detecting the sample surface and subsurface or internal defects without spoiling the metal parts. It is often used for testing sample quality and assisting the failure analysis process [9–11].

In the actual failure cases, fracture failure is the most important failure mode of mechanical parts. Therefore, the fracture surface observation method plays an important role in the failure analysis and is one of the most important and commonly used methods in the failure analysis process [12]. The stress condition and the failure process can be judged through observing the position of the fracture surface. By observing the characteristics of the fracture surface, the position of the crack source can be accurately determined [13], which provides an important basis for further analysis of the causes of subsequent fractures.

Railway fasteners, used for connecting the rails with the roadbed and playing a role of shock absorption, are important working parts in the railway transportation [14–16]. It will seriously affect the safety of the train if the fracture occurs. Based on the railway fastener cases failed in different ways, this chapter reveals the causes of the fracture from the perspective of macroanalysis and discusses the position and role of macroanalysis in the failure analysis.

2. Macroanalysis of the railway fastener fracture cases

2.1 The premature fatigue failure of fasteners caused by processing defects

Figure 1 shows the fracture condition of a rail fastening clip after the fatigue test of 4 × 105 cycles. However, according to the TB/T2329-2002 Chinese standard for the fatigue tests of rail fasteners, the samples should not fracture after 5 × 106 cycles. In order to find out the reasons of the premature failure, macroscopic analysis was conducted on the failed sample. As shown in **Figure 1a**, the fracture surface is not located in the position bearing the maximum stress during fatigue tests. The detailed observation reveals that a processing defect exists near the crack initiation region, as is shown in **Figure 1b**. This defect is mainly caused by the excessive extrusion of the hot plastic mold during induction heating, resulting in a local stress concentration at the defect. Subsequent quenching further increased the local stress at defects. During the fatigue tests, crack initiated from the stress concentrated position at the defects leading to the premature failure of the tested sample. As shown in **Figure 1c**, the characteristics of the fracture surface were revealed by the macroscopic analysis. The fracture surface shows the feature of a typical fatigue failure mode. The crack initiation region, crack expansion zone, and the final fracture region can be clearly observed on the fracture surface as marked in **Figure 1c**. Since the crack expansion zone occupies a large area, it indicates that,

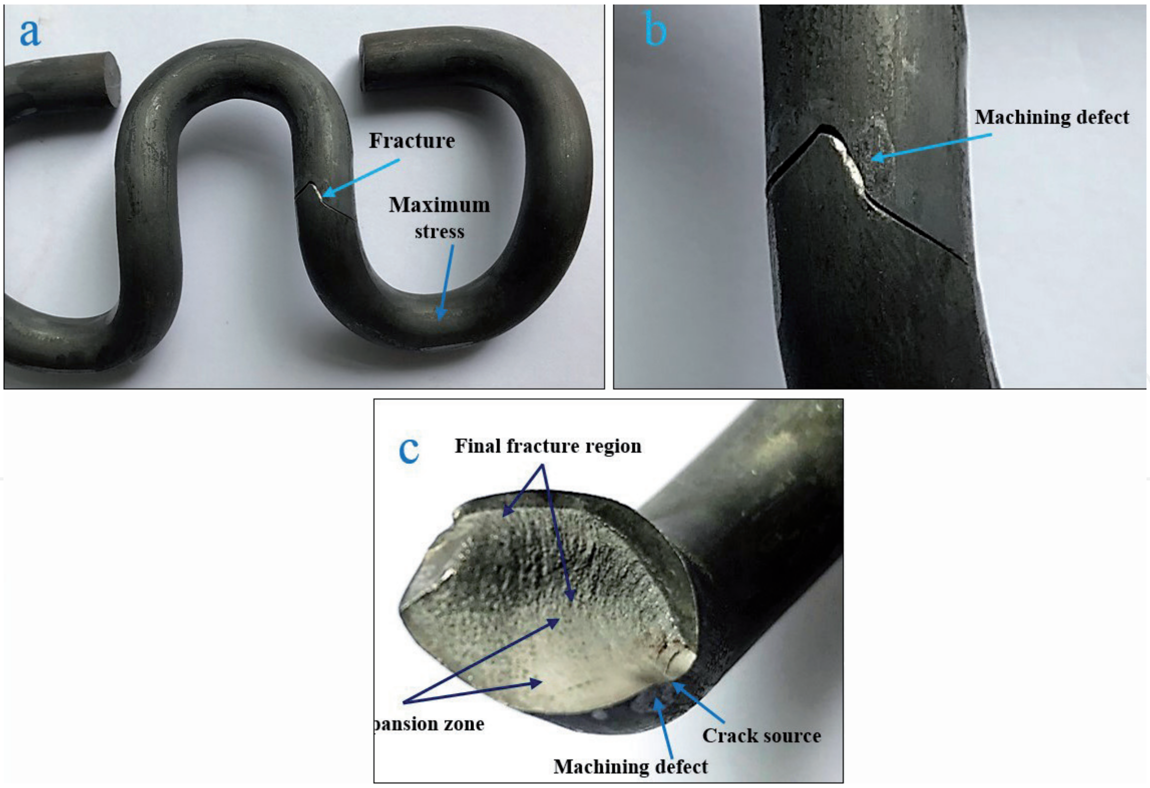

Figure 1.
Macroscopic analysis of the premature fatigue fractured rail fastening clip caused by surface processing defects: (a) the overall morphology of the fractured clip, (b) the processing defects near the crack initiation region, and (c) the morphology of the fractured surface.

after the cracks initiated at the surface defect, the sample undergoes a crack expansion period under the cyclic load before the final fracture. According to the theoretical equation reported in the literature [17, 18], the fracture strength of the tested rail fastening clip can be calculated based on the area of the instantaneous fracture zone and the maximum load applied.

In addition to the macroscopic analysis of the failed sample itself, analysis of the manufacturing environment, production conditions, and the service environment of the samples is also required. Sometimes, the external environments and service conditions can also play a key role on the sample failure. For example, oil was used as a common cooling medium in the heat treatment for many alloy steels. When the humidity in the heat treatment plant is high, the content of water in the quenching oil will increase continuously with the increasing of time. Therefore, the cooling rate will increase significantly when quenching is carried out in the oil with a certain concentration of water. When quenching alloy steels with a good hardenability, the internal stress will increase greatly due to the higher cooling rate, which leads to the increased risk of cracking after quenching of the sample [19].

2.2 The premature failure caused by improper heat treatments

Another example shows the effect of the producing process on the failure conditions of the rail fasteners. In order to improve production efficiency and reduce cost, the rail fasteners are subjected to medium frequency induction heating treatment before being deformed into the “M” shape. Then, the railway fasteners were quenched by the residual heat of induction heating after the thermoforming. In order to further reduce costs and improve efficiency, a company replaced the original intermediate frequency induction heating with high frequency induction heating in the production of railway fasteners. Because the heat generated by the high-frequency induction

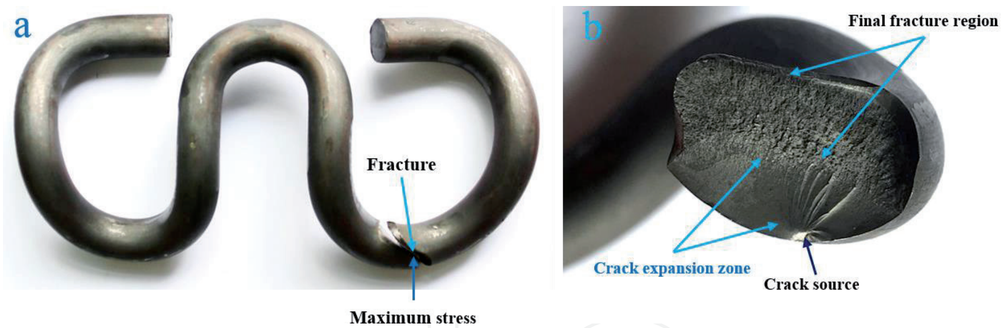

Figure 2.
The macroscopic morphology of the premature fatigue fracture samples processed by the high-frequency-inducing heating.

heating is more concentrated on the sample surface, it is easy to cause the uneven heating of the samples, resulting in large residual stress. In addition, the macroscopic factors such as insufficient heating time, insufficient heating power, or incorrect heating location of the sample may cause the inhomogeneity of the microstructure in the heat-treated samples. This type of microstructural inhomogeneity will lead to the property difference in certain regions, which can greatly reduce the fatigue life of the railway fasteners and cause the premature fatigue failure. **Figure 2** shows the fracture condition of railway fasteners, and the fatigue test is carried out after the high-frequency-inducing heating process. The premature failure occurred after 1.2 × 106 fatigue cycles (normally 5 × 106 cycles without fracture).

Compared with the case shown in **Figure 1** (case 1), the fracture position of the fastener is at the region bearing the maximum stress (as marked by the arrow in **Figure 2a**). The appearance of the failed region is normal, no obvious processing defect can be observed, and the fracture morphology also has typical fatigue fracture morphology including the crack initiation region, crack expansion zone, and the final fracture region [20, 21]. The area of the crack expansion region is comparable to that of case 1, but its fatigue life is much higher than the case 1, indicating that the fatigue crack growth rate is significantly lower than case 1. However, because the sample still did not reach the fatigue life of the typical fastener, it belongs to the abnormal fracture type. Different from case 1, the reason of the premature failure of case 2 cannot be directly found from the macroscopic analysis, and the microscopic analysis is therefore required. Since the fastener was produced by high-frequency heating rather than the original intermediate frequency heating, it is suspected that the uneven distribution of microstructure caused the premature fatigue fracture. Therefore, the metallographic microstructure analysis was carried out on the normal and the prematurely failed fastener at the position bearing the maximum stress during fatigue test. The position for extracting the sample parts and the corresponding microstructure are shown in **Figure 3**.

As shown in **Figure 3a** and **b**, the samples for microstructure observation of the normal and prematurely failed fasteners were cut from the same position near the fracture surface. The samples were ground by SiC paper and polished. The Nital solution (4% alcohol solution of nitric acid) was used as the etching solution. An optical microscope was used to complete the microstructure observation of the samples, and the results are shown in **Figure 3c**–**f**. **Figure 3c** and **d** shows the microstructure of the normal railway fastener after quenching and tempering in the medium temperature range; the typical tempered troostite and a small amount of ferrite can be clearly observed. The troostite and ferrite grains are fine, and they distributed evenly in the microstructure. **Figure 3e** and **f** shows the microstructure of the prematurely fractured samples. The obvious microstructure segregation

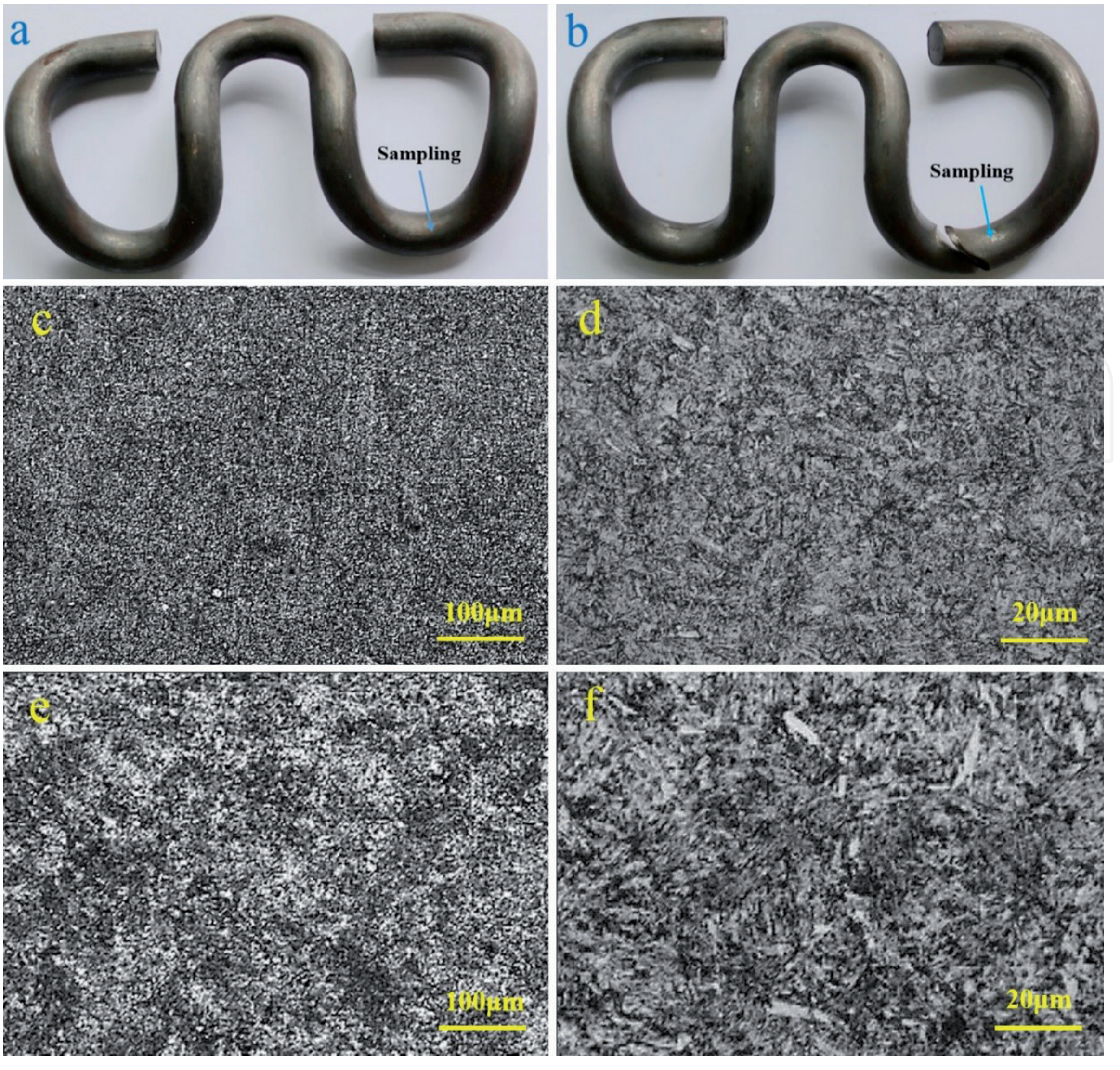

Figure 3.
The sample extraction position of normal (a) and prematurely failed railway (b) fasteners. (b, c) and (e, f) are the corresponding metallographic microstructure of the normal and prematurely failed fasteners, respectively.

can be observed from **Figure 3e**, which is caused by the large amount of dissolved cementite due to the fast heating rate of the high-frequency-inducing heating. The cementite came from the pearlite before heat treatment. As can be seen from **Figure 3f**, the grains are coarser, and in addition to the undissolved cementite, large block-shaped ferrite can also be observed. This is mainly due to the high heating rate and high temperature caused by the high-frequency-inducing heating. The rapid heating speed leads to the existence of a large amount of undissolved cementite. The heating temperature is too high, resulting in the formation of coarse microstructures [22]. This microstructural inhomogeneity can seriously affect the fatigue performance of the samples. Cracks are more prone to initiate at the microstructure with poor mechanical properties under the applied cyclic load, resulting in the premature fatigue fracture. This example shows that in the process of failure analysis, in addition to the analysis of the macroscopic characteristics of the sample, the macroscopic factors such as the production environment and the service environment of the sample parts are also important and sometimes are important causes of sample failure. It is sometimes difficult to directly and accurately determine the cause of failure from macroanalysis. This requires a combination of macroanalysis and microanalysis to achieve the accurate failure analysis results.

2.3 The effect of the service condition on the failure of railway fasteners

In addition to the manufacturing processes, the service environment is sometimes critical to the macroanalysis of failures. For example, in the following case, an e-type fastener widely used in the subway track has a premature fatigue fracture when it has been used in practice for about 1 year (the designed service life is 10 years). This kind of fastener breakage will cause major safety hazards to the safe operation of the train. It is necessary to analyze the causes of the failure in order to eliminate potential dangers in time and ensure the safe operation of the train. In order to analyze the cause of the fracture, a macroscopic observation of the broken subway track fastener clip was first carried out; the results are shown in **Figure 4**.

As can be seen from **Figure 4a**, the breaking position located at the root of the straight section of the fastener, and this straight section is installed in the fixed slot. The fracture happened at the boundary between the straight section and the residual curved part, in which the maximum stress is loaded in the broken position in the actual working condition. A detailed observation of the sample surface reveals obvious wear marks. Moreover, the wear marks are in the same direction along the transverse arc of the fastener sample (see **Figure 4b**). As can be observed from the magnified view shown in **Figure 4c**, the wear marks have a certain depth, and their propagation direction is consistent. Based on the direction and depth of the wear scar, it can be preliminarily concluded that the wear scars on the surface of the straight section of the railway fastener were caused by the relative rotation with the spring clip slot it contacted with. However, in the normal circumstances, this type of rotation is not allowed, because the rotation will reduce the pressure between the fastener and the railway track, affecting the train safety. Combined with the relatively deep wear marks, the broken fastener is subjected to a large external force before failure. The reason causing this large external force can only be determined by the on-site investigation with the understanding of the service situation.

According to the investigation of the service scene, the subway operates along a circle line, and the fasteners with premature fatigue failure occurred mostly at or near the curve region of the railway track. This indicates that in addition to the force of caused by the vibration of the track when a train passed, the spring bar is also subjected to the centrifugal force when the train is adjusting directions. Under the combined force of the vibration and the centrifugal force, the fastener rotated relatively in the slot, resulting in a surface with a consistent direction of wear scar. After multiple friction, the wear marks at the position where the fastener is in contact with the edge of the slot became deeper and deeper, and thus fatigue cracks were

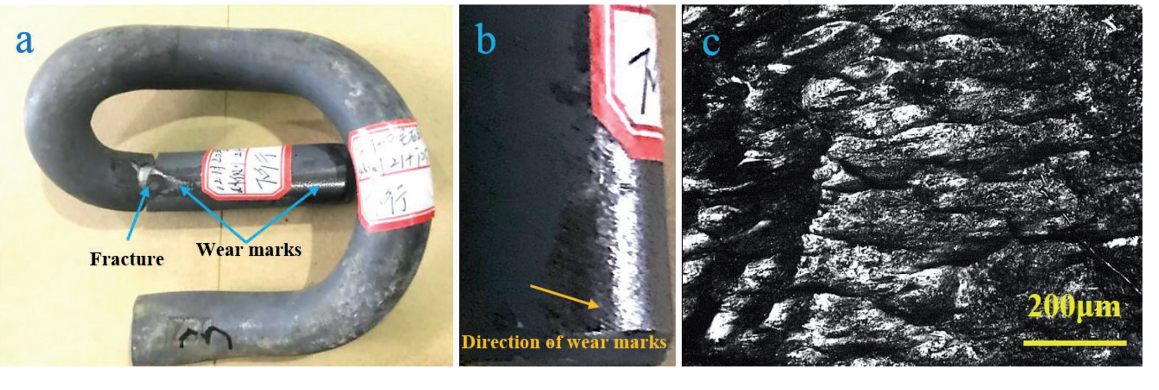

Figure 4.
The macroscopic morphology and surface wear scars of the fractured metro fastener: (a) the macroscopic morphology of the failed fastener showing the position of the fracture surface and the wear marks, (b) the obvious wear scar that can be observed on the surface of the straight section of the fastener clip, and (c) the enlarged view of wear scar.

DOI: http://dx.doi.org/10.5772/intechopen.89262

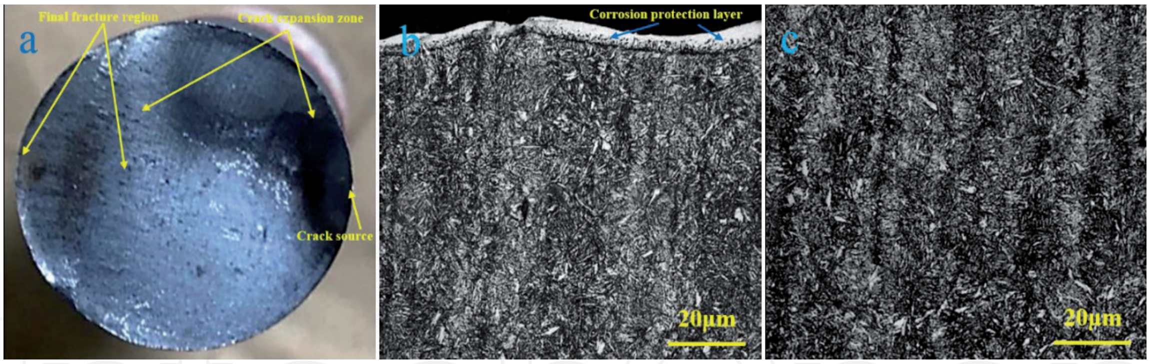

Figure 5.
The macroscopic morphology of the fracture surface and the microstructure of the samples near the fracture surface: (a) the fracture surface morphology, (b) the cross-sectional microstructure of the sample near the fracture surface, and (c) the microstructure of core region of the sample near the fracture surface.

generated. Due to the large external force, the crack spreads rapidly, resulting in the final premature fracture failure of the fastener. In order to more accurately determine the cause of the failure of the elastic strip, combined with the macroscopic analysis of the fracture surface, the metallographic microstructures near the fracture surface were further observed and analyzed. The results are presented in **Figure 5**.

From the macroscopic analysis of the fracture surface as shown in **Figure 5a**, the crack initiation region has a certain area, and the color is dark blue and slightly black, which is mainly due to the inconsistent deformation of the elastic strips on both sides of the crack, and the oxidation of the fracture surface resulted from the temperature rising caused by the relative extrusion and friction. This again proves that the elastic strips underwent severe torsional deformation during actual service. From the morphology of the crack extension area in **Figure 5a**, the extended area has obvious macroscopic fan-shaped stripes, and the spacing between the strips is large. The spacing between the fan-shaped stripes is large, which indicates that under the load of the torsion force, the severe wear scars were first produced on the surface where the stress reaches the maximum value. Then, micro-cracks were formed in the most severely worn areas. Under the combined load caused by the vibration of the rail tracks and the centrifugal force, the cracks expanded rapidly, resulting in the final premature fracture. At the same time, samples near the fracture surface were extracted for the preparation of the metallographic sample. The surface and center microstructure of the surface of the prepared samples is shown in **Figure 5b** and **c**. It can be observed that the tempered troostite (or tempered torsite) and a small amount of ferrite are the main microstructure of the elastic stripe after quenching with medium temperature tempering, which is the normal microstructure. A layer of anticorrosion treatment can be observed on the surface, which is a conventional treatment for railway fasteners.

The early failure of the railway fasteners caused by the external service environment indicates that in addition to considering the material selection and processing technology and performance of the product, the actual working environments should also be taken into consideration. In order to ensure the operation safety of the equipment, the design and manufacture of the product can be improved based on the actual working condition of the components. Only then can the safety factor in the actual service process be increased.

3. The function of macroscopic analysis in the failure analysis of railway fastening clips

Based on the above analyses of several failure cases of the railway fasteners, it can be concluded that the macroscopic analysis plays a key role in the process of failure analysis. Combined with the macroscopic characteristics of the sample, the failure site, the background data, the service environment, and other macro factors, the mode and cause of the failure can be preliminarily judged after careful observation and analysis. On the basis of macroanalysis, with the help of modern analytical test methods, microanalysis, and computer simulation techniques, the failure mechanism can be further explored to accurately determine the cause of failure. Moreover, the solutions can be given based on the causes of the failure for avoiding the occurrence of disasters.

In Section 2.1, if the macroscopic analysis is not carried out, the processing defects near the crack source cannot be found, and the causes of the premature fracture of the fasteners will not be accurately determined, which will have a serious impact on the production and sales of the products. If the unqualified products with surface defects flow into the market, it will cause serious danger to the safety of the train operation. Moreover, as discussed in Section 2.2, combined with the macroscopic factors of the changes of production conditions (medium-frequency induction heating to high-frequency induction heating), it is preliminarily believed that the premature fatigue failure of the railway fastener is caused by the uneven heating. Then, under the guidance of the macroanalysis, the microscopic analysis is carried out, and the cause of the premature fatigue failure is finally determined. Based the failure analysis results, the manufacturers were told to make improvements in time to avoid major economic losses and safety hazards. Similarly, in the example of Section 2.3, the causes of the fastener premature fracture were determined by combining the macroscopic damage on the appearance of the failed fastener with the complex force during service, through the investigation of the on-site service environment. It provides an important basis for the further improvement of the performance of railway fasteners.

All in all, macroanalysis is the first and most important step in failure analysis. Firstly, through macroanalysis, the position of the failure and the failure mode can be accurately determined, which lays a foundation for further analyzing the failure causes. Secondly, with the understanding of the failure location and the failure mode, the fracture reasons can be determined based on the force analysis, the service environment, and the manufacturing processes. Finally, combined with the verification experiments, microanalysis methods and computer simulation, the causes of the failure can be accurately determined, and solutions and suggestions can be given to eliminate potential safety hazards and avoid disasters.

With the development of modern technology and manufacturing equipment, product defects caused by design, materials, and processing technology are becoming less and less, and accidents caused by the product failure are also declining year by year. However, the assembly of components, special service environment, sudden natural disasters, etc. will seriously affect the operational safety of various types of equipment and facilities, in which special attention should be paid in the failure analysis. In particular, in recent years, with the development of science and technology, a large number of high-performance new materials and products are widely used, which brings new challenges to failure analysis. It is also necessary to continuously develop and innovate failure analysis methods, means, and concepts and lay the foundation for adapting to accurate failure analysis in the new situation and environment.

Acknowledgements

The authors gratefully acknowledge financial support from the Sichuan Education Reform Project (No. JG2018-158).

Author details

Guodong Cui*, Shuaijiang Yan, Chengsong Zhang, Dazhi Chen and Chuan Yang
School of Materials Science and Engineering, Southwest Jiaotong University, Chengdu, China

*Address all correspondence to: gdcui@swjtu.edu.cn

References

[1] Zhang T, Bao R, Fei B. Load effects on macroscopic scale fatigue crack growth path in 2324-T39 aluminium alloy thin plates. International Journal of Fatigue. 2014;**58**:193-201. DOI: 10.1016/j.ijfatigue.2013.04.014

[2] Tang XS, Wei TT. Microscopic inhomogeneity coupled with macroscopic homogeneity: A localized zone of energy density for fatigue crack growth. International Journal of Fatigue. 2015;**70**:270-277. DOI: 10.1016/j.ijfatigue.2014.10.003

[3] García-Martínez M, García de Blas Villanueva FJ, Valles González MP, Pastor Muro A. Failure analysis of the rod-end bearing of an actuating cylinder. Engineering Failure Analysis. 2019;**104**:292-299. DOI: 10.1016/j.engfailanal.2019.06.006

[4] Vukelic G, Brcic M. Failure analysis of a motor vehicle coil spring. Procedia Structural Integrity. 2016;**2**:2944-2950. DOI: 10.1016/j.prostr.2016.06.368

[5] Guo R, Xue S, Zheng L, Deng A, Liu L. Fracture failure analysis of DY08 aluminum alloy elastic coupling. Engineering Failure Analysis. 2019;**104**:1030-1039. DOI: 10.1016/j.engfailanal.2019.06.074

[6] Vander Voort GF. Metallography and failure analysis. Materials Characterization. 1994;**33**:193. DOI: 10.1016/1044-5803(94)90044-2

[7] Xu J, Sun Y, Liu B, Zhu M, Yao X, Yan Y, et al. Experimental and macroscopic investigation of dynamic crack patterns in PVB laminated glass sheets subject to light-weight impact. Engineering Failure Analysis. 2011;**18**:1605-1612. DOI: 10.1016/j.engfailanal.2011.05.004

[8] You JH. Triple-scale failure estimation for a composite-reinforced structure based on integrated modeling approaches. Part 2: Meso- and macroscopic scale analysis. Engineering Fracture Mechanics. 2009;**76**:1437-1449. DOI: 10.1016/j.engfracmech.2008.10.017

[9] Dwivedi SK, Vishwakarma M, Soni PA. Advances and researches on non destructive testing: A review. Materials Today: Proceedings. 2018;**5**:3690-3698. DOI: 10.1016/j.matpr.2017.11.620

[10] Brown M, Wright D, M'Saoubi R, McGourlay J, Wallis M, Mantle A, et al. Destructive and non-destructive testing methods for characterization and detection of machining-induced white layer: A review paper. CIRP Journal of Manufacturing Science and Technology. 2018;**23**:39-53. DOI: 10.1016/j.cirpj.2018.10.001

[11] Starke P, Wu H. Use of non-destructive testing methods in a new one-specimen test strategy for the estimation of fatigue data. International Journal of Fatigue. 2018;**111**:177-185. DOI: 10.1016/j.ijfatigue.2018.02.011

[12] Kobayashi T, Shockey DA. The relationship between fracture surface roughness and fatigue load parameters. International Journal of Fatigue. 2001;**23**:135-142. DOI: 10.1016/S0142-1123(01)00149-9

[13] Park CY, Grandt AF. Effect of load transfer on the cracking behavior at a countersunk fastener hole. International Journal of Fatigue. 2007;**29**:146-157. DOI: 10.1016/j.ijfatigue.2006.01.014

[14] Li L, Thompson D, Xie Y, Zhu Q, Luo Y, Lei Z. Influence of rail fastener stiffness on railway vehicle interior noise. Applied Acoustics. 2019;**145**:69-81. DOI: 10.1016/j.apacoust.2018.09.006

[15] Wei X, Yang Z, Liu Y, Wei D, Jia L, Li Y. Railway track fastener defect

detection based on image processing and deep learning techniques: A comparative study. Engineering Applications of Artificial Intelligence. 2019;**80**:66-81. DOI: 10.1016/j.engappai.2019.01.008

[16] Cao Z, Brake MRW, Zhang D. The failure mechanisms of fasteners under multi-axial loading. Engineering Failure Analysis. 2019;**105**:708-726. DOI: 10.1016/j.engfailanal.2019.06.100

[17] Zhang J, Song Q, Zhang N, Lu L, Zhang M, Cui G. Very high cycle fatigue property of high-strength austempered ductile iron at conventional and ultrasonic frequency loading. International Journal of Fatigue. 2015;**70**:235-240. DOI: 10.1016/j.ijfatigue.2014.09.021

[18] Yu M, Wei C, Niu L, Li S, Yu Y. Calculation for tensile strength and fracture toughness of granite with three kinds of grain sizes using three-point-bending test. PLoS ONE. 2018;**13**:e0180880. DOI: 10.1371/journal.pone.0180880

[19] Ma Z, Wang Y, Ji S, Xiong L. Fatigue properties of Ti-6Al-4V alloy friction stir welding joint obtained under rapid cooling condition. Journal of Manufacturing Processes. 2018;**36**:238-247. DOI: 10.1016/j.jmapro.2018.10.006

[20] Burcham MN, Escobar R, Yenusah CO, Stone TW, Berry GN, Schemmel AL, et al. Characterization and failure analysis of an automotive ball joint. Journal of Failure Analysis and Prevention. 2017;**17**:262-274. DOI: 10.1007/s11668-017-0240-4

[21] Robin MC, Delagnes D, Logé R, Bouchard PO, Da Costa S, Monteagudo-Galindo M, et al. Thermo-mechanical fatigue behaviour of welded tubular parts made of ferritic stainless steel. International Journal of Fatigue. 2013;**54**:84-98. DOI: 10.1016/j.ijfatigue.2013.04.004

[22] Xu L, Chen L, Sun W. Effects of soaking and tempering temperature on microstructure and mechanical properties of $65Si_2MnWE$ spring steel. Vacuum. 2018;**154**:322-332. DOI: 10.1016/j.vacuum.2018.05.029