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Case study

A failure study of the railway rail serviced for heavy cargo trains

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ABSTRACT

In this case study, a failed railway rail which was used for heavy cargo trains was investigated in order to find out its root cause. The macroscopic beach marks and microscopic fatigue striations were not observed by macro and microscopic observations. The chevron patterns were observed by macro observations. The crack origin was at the tip of chevron patterns. The fan-shaped patterns, cleavage step and the river patterns were observed at the crack origin, which demonstrated the feature of cleavage fracture. The metallurgical structures at the crack origin were pearlite and ferrite networks. The crack is supposed to be initiated from the weaker ferrite networks. Given all of that, the failed railway rail is considered to be caused by overload. It is of great importance to improve the welding technology, and control the load of train in order to prevent similar failure in future.

1. Introduction

With the development of high-speed and heavy-load railway, much higher requirements are put forward for the comprehensive properties of steel rails [1]. Since fracture accidents of steel rail threaten the safety of railway transportations directly, more and more attention is paid to the quality of rail steel. The fatigue fracture is the main failure form of steel rail. Despite substantial advantages in design, materials and non-destructive inspection, fatigue propagation in and failure of railway components remains an important issue for safety engineering which is also emphasized by a number of accidents over the last decades [2,3]. At the background of an increased volume of traffic, higher traffic speeds and higher axle loads, reliable damage tolerance design and effective maintenance methods have to be established. Therefore, failure analysis of the steel rail is very critical.

In addition to the fatigue load, rails are also subjected to other high mechanical loads and harsh environmental conditions. The main loading components are rolling contact pressure, shear and bending forces from the vehicle weight, thermal stresses due to restrained elongation of continuously welded rails and residual stresses from manufacturing (roller straightening) and welding in the field (Fig. 1) [2]. Welding is indispensable in the railway rail. Today, the most common rail

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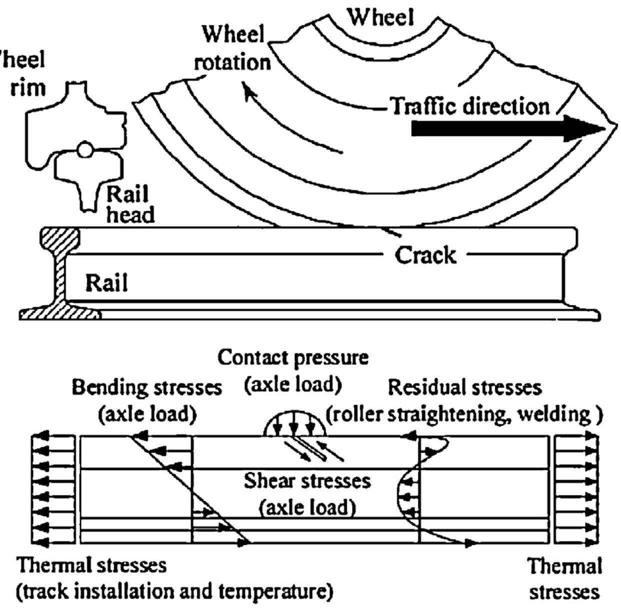

Fig. 1. Loading components acting at a continuously welded rail during vehicle passing [2].

welding processes are flash-butt welding, aluminothermic welding, gas pressure welding and enclosed arc welding. Among them aluminothermic welding of rails is used widely within the railway industry for in-track welding during re-rail and defect replacement. The process provides flexibility and low capital cost, but suffers from variable quality in finished welds, due to the inherent limitations of the processes used, and their operator dependency [4]. Therefore, it is harder to control the quality of welded points. Statistics show that during 18-month period aluminothermic weld failures comprise approximately 75% of all broken rail reports for the Newman mainline [4]. In response to failures in aluminothermic welds, and in recognition that such welds represent one of the main risks for a catastrophic derailment, it is necessary to develop an improved rail welding process which meets the performance demands of higher axle loads.

In the present paper, a fractured railway rail which was used for cargo trains was analyzed to find out its failure cause. In the end, a conclusion was reached after performing macroscopic inspections, chemical analysis, SEM observations, and metallographic examinations.

2. Background

Firstly, it is necessary to collect as much as possible the information on the previous history of the fractured railway rail. The fractured railway rail was provided by the railway administration staff. According to the introductions, the railway rail came into service in May 2005. The railway rails were butt-welded together by the aluminothermic welding process, and the postweld heat treatment was not conducted. The railway rail was found to be fractured in December 2011 when it was in winter. During 2005–2011, this route was serviced for heavy cargo trains. The type of the rail steel was GB P60U75V as introduced by the railway administration staff.

3. Results

3.1. Macroscopic inspections

The macroscopic fracture morphology of the fractured railway rail was shown in Fig. 2. The dimensions of the railway rail which were provided by the client were shown in Fig. 2(a). It was found that the fracture surface was basically clean and fresh, which demonstrated that the corrosion of the fracture surface was not heavy. The top in Fig. 2(a) was the railhead contacted with wheel rim, the bottom was the rail bottom contacted with the ballast, the middle part between railhead and rail bottom was the rail web. We could also found that the fracture surface at the rail bottom was close to the weld bead and relatively flat (Fig. 2(b)), and that the fracture surface was approximately perpendicular to the longitudinal direction of the railway rail. The fracture surface at the rail web was approximately arched when observed from the profile (Fig. 2(b)). The fracture surface at the railhead was inclined at about 60° to the longitudinal direction of the railway rail. The fracture surface at the railhead was very rough; therefore, it was deduced that this part might be caused by the final instant fracture instead of the fracture origin. There was a darkly fan-shaped area at the left bottom of Fig. 2(c). A small bright spot was observed next to the darkly fan-shaped area (Fig. 2(c)). As introduced by the railway administration staff, the bright spot was not separated yet when the railway rail failed.

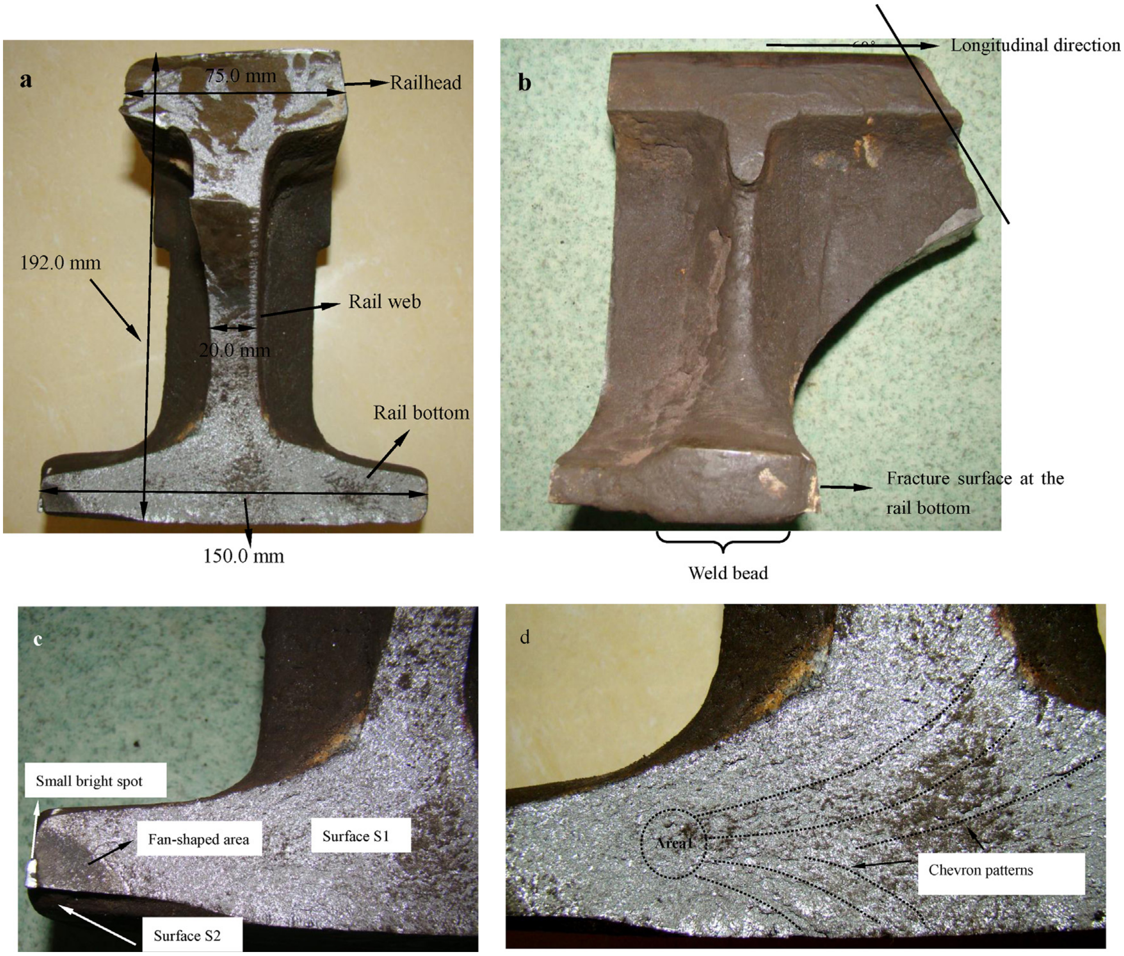

Fig. 2. The macroscopic morphologies of the failed railway rail. (a) The front view, (b) the lateral view, (c) the macroscopic morphology of the rail bottom, and (d) the chevron patterns and crack origin at the fracture surface of rail bottom.

Since the railway rail was subjected to cyclic loading and served about 6 years, it is rational to consider that this railway rail might be failed due to fatigue, even in giga cycle fatigue regime [5–7]. The arc boundary of fan-shaped area looks like a beach mark when observed macroscopically, as seen in Fig. 2(c). Then it can be deduced that the crack origin might be at the corner of darkly fan-shaped area (viz., the small bright spot as shown in Fig. 2(c)). However, taking into account that the small bright spot was next to darkly fan-shaped area, it is obviously to deduce that the small bright spot would not be the crack origin. The beach marks which were the classical features of metal fatigue were not observed from the macroscopic observations (the arc boundary of fan-shaped area is actually not a beach mark, we will discuss that hereinafter). However, the chevron patterns can be clearly observed at the fracture surface of rail bottom (Fig. 2(d)). Therefore, we can deduce that the crack origin should be at the tip of chevron patterns (area 1), and the crack growth direction is along the diverging direction of river patterns, as shown in Fig. 2(d). It can be deduced from the flat fractography and chevron patterns that the macro fracture feature is brittle fracture.

3.2. Chemical analysis

The sample used for chemical analysis which was sampled from railhead was analyzed by ZSX Primus II X-ray fluorescence spectrometer. The results were shown in Table 1. It was demonstrated that the chemical compositions of the

Table 1
The chemical compositions of failed railway rail (mass%).

Steels	C	Mn	Si	S	P	V
The rail steel	0.74	0.96	0.68	0.0035	0.016	0.062
GB P60U75V	0.71–0.80	0.70–1.05	0.50–0.80	≤0.030	≤0.030	0.040–0.12

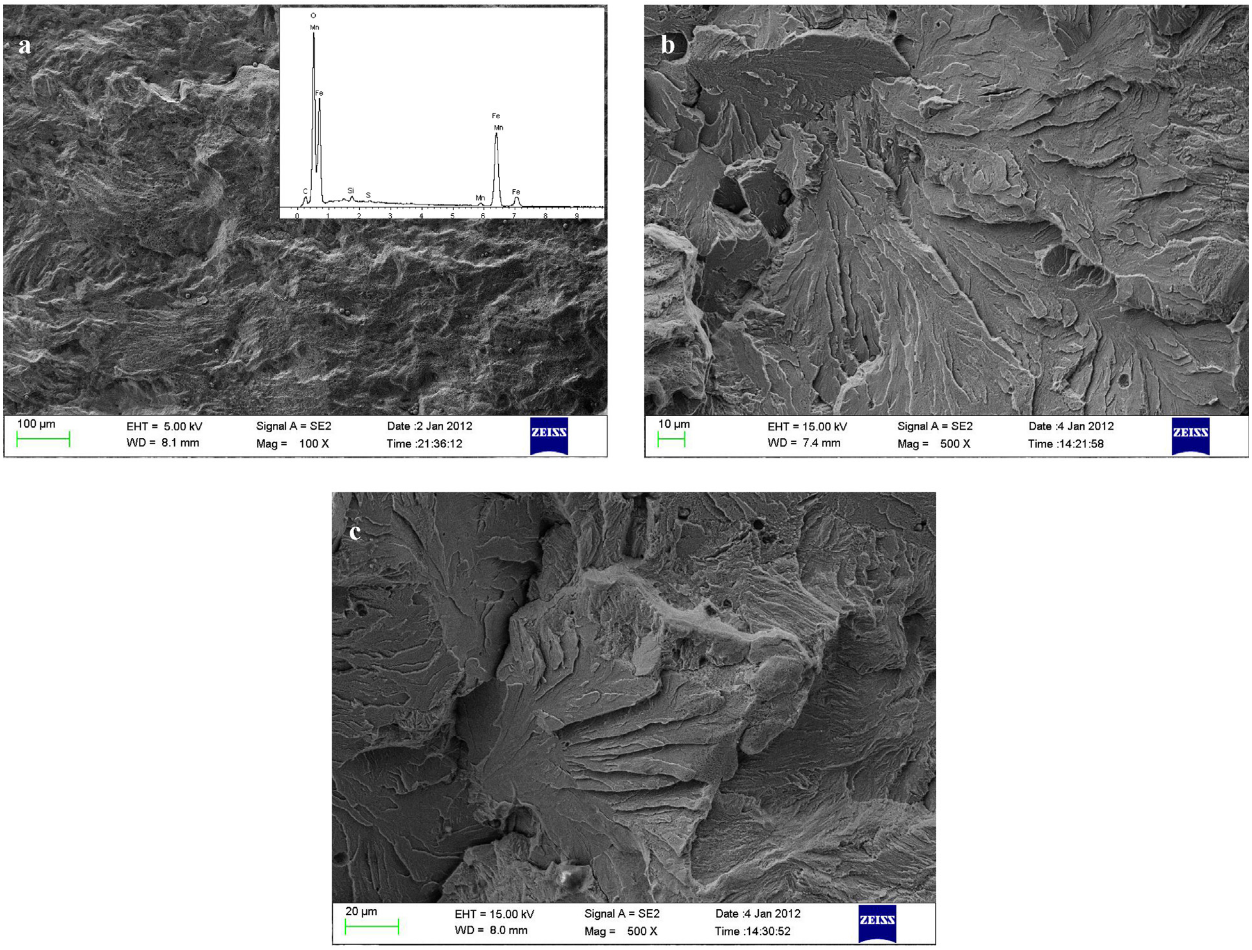

Fig. 3. The microscopic morphologies of the fracture surface. (a) Inside fan-shaped area, (b) area 1, and (c) the area of chevron patterns.

rail steel were in accordance with the standard of P60U75V [8]. Therefore, the compositions of the rail steel were normal.

3.3. SEM observations

The fracture surface at the rail bottom, viz. surface S1 (as shown in Fig. 2(c)), was cut from the failed railway rail, and then cleaned by alcohol and dichloroethane. After that, surface S1 was observed by ZEISS-SUPRA 55 field emission scanning electron microscope (FESEM) in detail. The morphology inside the darkly fan-shaped area is shown in Fig. 3(a) which shows a relatively flat surface. The qualitative chemical compositions of this area are analyzed by EDX, also shown in Fig. 3(a). Higher oxygen contents were detected, which demonstrates that this area was oxidized heavily. The typical morphology in area 1 is shown in Fig. 3(b) which shows the typical feature of cleavage fracture. The fan-shaped patterns, cleavage step and river patterns which are the typical feature of cleavage fracture are observed in this figure. Fatigue striations which were the typical microscopic features of metal fatigue were not observed in the fracture surface. The micro fractography of the chevron patterns area is shown in Fig. 3(c) which is similar to Fig. 3(b). The fracture surface outside the darkly fan-shaped area is clean and fresh, almost no oxygen is detected. Combined with the experimental results outside and inside the darkly fan-shaped area, it can be deduced that the darkly fan-shaped area might be an incomplete fusion area during welding.

3.4. Metallurgical observations

Firstly, surface S2 (as shown in Fig. 2(c)) was polished to observe the distribution of inclusions. It was shown in Fig. 4 that some bigger slag inclusions with sharp angular shape were observed at surface S2 close to the fracture surface at the rail bottom. The size of these slag inclusions was about at least 126 μm defined by Murakami's effective projective area model [9]. EDX demonstrated that the composition of these slag inclusions was alumina. After etched by 3% nital the metallurgical structure of surface S2 close to the fracture surface was observed by optically metallurgical microscope (OMM). Continuous

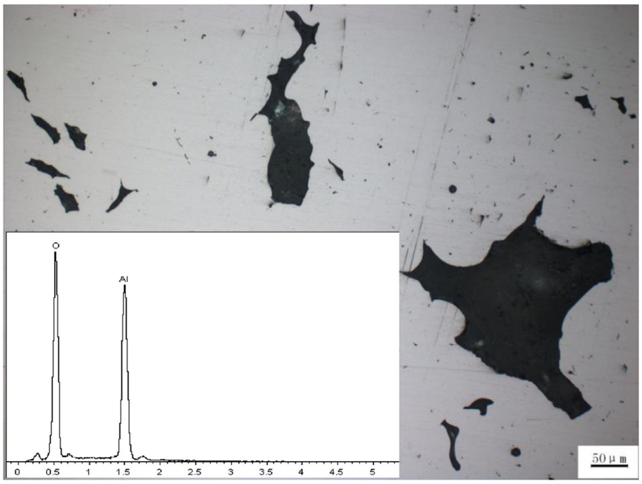

Fig. 4. The morphologies of the slag inclusions and EDX results.

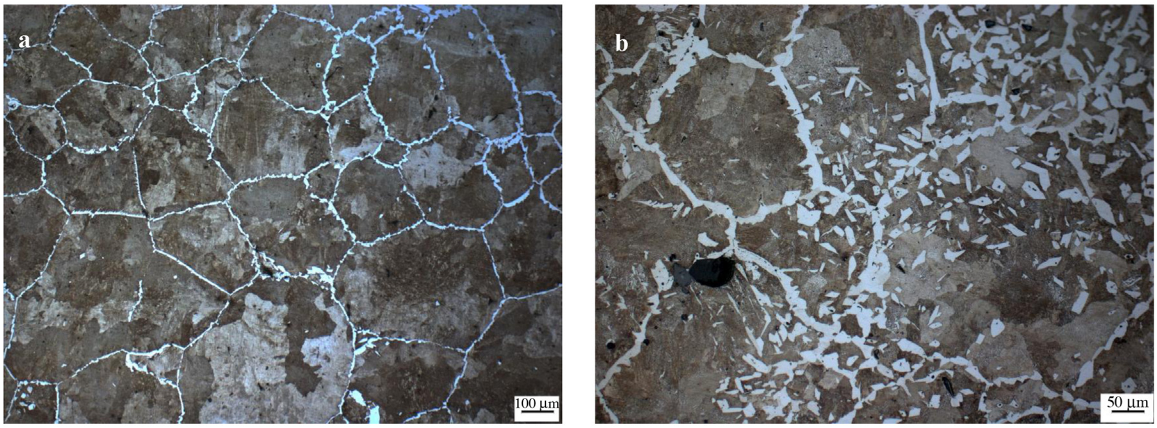

Fig. 5. (a) The metallurgical structures of surface S2 close to the fracture surface and (b) the metallurgical structures in area 1.

ferrite networks and pearlite colonies were observed, as shown in Fig. 5(a). It was also demonstrated from Fig. 5(a) that the size of pearlite colony, viz. the area surrounded by continuous ferrite networks, was rather heterogeneous. The biggest size of the pearlite colony was about 726 μm in diameter, the smallest size 68 μm. After making an obvious mark at the crack origin site (area 1) on surface S1, surface S1 was polished and etched by 3% nital in order to observe the metallurgical structures. The metallurgical structures in area 1 were pearlite, continuous ferrite networks and a mass of ferrite fragments distributed inside the pearlite colonies, as shown in Fig. 5(b). Considering the weaker strength of ferrite distributed like nets compared with pearlite; it can be deduced that the crack might be initiated from the ferrite networks.

4. Discussion and analysis

As introduced in Section 1, the railway rail was mainly subjected to cyclic loading. In this case study, the macroscopic beach marks and microscopic fatigue striations were not observed at the fracture surface. In addition, the typical chevron patterns were observed. And the feature of cleavage fracture was observed at the tip of chevron patterns. Given all of that, we can draw a conclusion that the railway rail is mainly caused by overload even though it is subjected to cyclic loading. Considering the abnormal metallurgical structures (ferrite networks distributed along the grain boundaries) at the crack origin, the crack is supposed to be initiated from the weaker ferrite networks which are caused by welding. Therefore, it is much needed to eliminate the ferrite networks by improving the welding technology.

4.1. Stress analysis

In this case study, this railway rail was mainly subject to alternate bending stress due to vehicle weight, as shown in Fig. 1. It is shown from Fig. 1 that the rail head was subject to compressive stress and the rail bottom was subject to tensile stress.

Therefore, the rail bottom was subtle to fail from the point of view of mechanics. The rail bottom can be approximately considered to subject fatigue load in the longitudinal direction of railway with $R = 0$ (R was stress ratio), and the applied stress at the lower bottom of rail was approximately the maximum. In view of the heavily incomplete fusion area (darkly fan-shaped area in Fig. 2(a)) at the bottom corner of rail bottom, the crack was supposed to be initiated from this incomplete fusion area. Nevertheless, in fact it is not the case. The residual stress must be considered. In addition to the residual tensile thermal stress due to track installation and temperature (as shown in Fig. 1), the welding residual stress was also of great importance. The welding residual stress was usually detrimental; therefore, many rail failures were initiated from the weld [4]. The residual stress and applied stress due to the train's gravity can be superimposed together. The superimposed stress will induce the failure of the rail under certain conditions.

4.2. The role of fatigue

The railway rail is failed by overload; however, we cannot completely deny the role of fatigue. The damage trace generated by cyclic loading was not observed at the crack growth area; however, the fatigue damage was almost inevitable by taking the longer service life into account (about 6 years). On the other hand, usually the fatigue damage cannot be easily detected due to the complicated working situations of a component.

4.3. Suggestions

The failed railway rail was caused by overload. The crack origin was the ferrite net induced by inadequate welding technology. Therefore, in order to prevent similar failures in future, the welding process must be improved. For example, pro and postweld heat treatments should be conducted to eliminate the bigger slag inclusions and ferrite networks along the grain boundaries. On the other hand, it is of great importance to control the load of train.

5. Conclusions

This failed railway rail is caused by overload. The crack is initiated from the weaker ferrite networks which are induced by inadequate welding technology. It is of great importance to improve the welding technology, and control the load of train in future.

Acknowledgments

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