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FAILURE OF A LOW RAIL IN A CURVED RAILWAY TRACK SUBJECT TO LONG TERM RAIL-WHEEL INTERACTIVE WEAR

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ABSTRACT

This paper investigated the failure of a rail that had been in service for approximately 25 years in Tasmania, Australia. A segment of the rail was taken from the site on a curved railway track. From its service history, it was found that the maximum train speed over that period was around 35km/h. However, approximately one third of the movements were at a speed less than 20km/h due to the fact that the rail was located on the steepest section of the line. Visual examination on the rail sample revealed that the rail had experienced mixed traffic conditions during the service history. Mushrooming shaped plastic flow occurred in the railhead. The chemical composition of the rail was analysed using the optical emission spectroscopy method. Metallurgical observation on the rail sample and a hardness test were conducted, aiming to investigate the root cause of the failure. The aim of this study was to conduct the failure analysis of the rail and to provide knowledge regarding the selection of a sustainable type of rail for this application.

KEYWORDS

Rail steel, rolling-sliding, optical microscopy, hardness.

INTRODUCTION

Rail failure is a common problem around the world. The inspection and maintenance costs remain an economic burden for many railway operations. It was reported that the rail associated problem costs 2 billion Euro per annum in the European Union (Cannon et al. 2003), and the North American Railroads spent about $600M annually on purchasing new rails for the replacement of deteriorated rails in the early 1980s (Tyfour et al. 1995). In Australia, the Government allocated over $193M between 2009 and 2013 to maintain the rail network that had experienced multiple derailments and other safety issues (Midson 2012).

Common types of rail defects include excessive wear due to rail/wheel contact, cracks and surface spalling in railhead due to rolling contact fatigue and plastic flow of railhead on curved tracks (Clayton et al. 1983). The amount of rail wear is influenced by various elements, such as rail type (weight, grade, chemical composition and microstructure), design factors (sleeper type, track geometry) and service conditions (axle loads, annual tonnage and train speed) (Bogdaniuk et al. 2003). The rail cant has a significant influence on the low rail in a curved track. An increase in rail cant results in wear on the low rail on a curved track (Jin et al. 2009). The extent of lateral wear on a low rail in curved tracks depends on the curve radius, design cant and train speed. The amount of the cant is designed to suit certain train speed. Slower trains tend to make flange contact with the low rail on curves, while faster trains tend to ride outwards and make contact with the high rail. When a slow wagon passes a curve with a steep slope, the weight of the wagon is transferred to the low rail and the railhead widens (Sadeghi & Akbari 2006). To prevent damage to low rails, many high-speed lines do not permit slower freight trains, particularly with heavier axle loads. It was reported that the maximum static axial loads in Europe range from about 21 to 25t. In Australia, axle loads of about 37t have been reported (Cannon et al. 2003).

The rail sample in this study was provided by the Rail Safety Unit of the Department of Infrastructure, Energy and Resources of Tasmania, Australia. According to the information provided by the Rail Safety Unit, the rail sample was taken from a rail track that had been in service for approximately 25 years. During this period, the maximum axle load that the rail had experienced would have been 18t, with approximately 1.5 million tons of traffic per annum. Before the rail was brought into Tasmania, it would have been in the track for up to 60 years. Beyond this, the exact history of the rail was unknown. The maximum train speed in that time would have been 35km/h. However, approximately one third of the movements would have been at a speed less than 20km/h. This was due to the rail was located on the steepest section of the line. The rail sample was a part of the lower rail in a curve with a radius of 100 metre and a designed cant of 40mm. The aim of this study was to investigate the crystalline microstructure of the rail sample and to examine defects and cracks. It will help to understand the condition of the rail in the network and the circumstances surrounding the derailment that this rail was involved with.

VISUAL EXAMINATION

It can be seen from the rail sample shown in Figure 1 that the rail experienced severely worn on the railhead with a large amount of lateral plastic deformations and material loss.

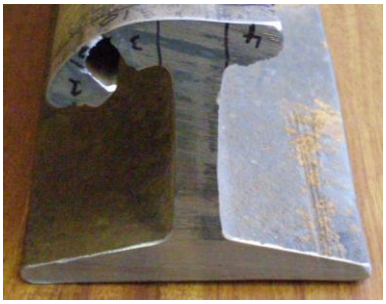

Figure 1. A cross sectional view of the rail sample

The deformed rail profile was compared with the undeformed rail sections as shown in Figure 2. The red line in Figure 2 shows the profile of a 80lb ASCE rail manufactured by HarmerSteel (2009). About 20mm thick rail material had been lost from the railhead due to plastic deformation and wear. The plastic flow was accompanied by a crack that caused the separation of a part of rail from the railhead. The crack appeared to be initialized in the horizontal direction in a location below the rail surface. It seemed that a part of the railhead was pushed away by a shear force generated by the plastic flow on the railhead. The geometrical profiles on both sides of the crack had similar profiles. A mushrooming shaped plastic deformation happened at the end of the railhead. The mushrooming type of deformation was regarded as a common type of rail degradation (Reddy et al. 2008).

In addition to plastic flow, flake-like wear debris was also observed on the surface of the railhead. This failure mode was called plastic ratcheting by Kapoor (1997). Franklin & Kapoor (2007) explained that ratcheting occurred due to the load exceeded the plastic shakedown limit of the rail, causing large plastic shear strains in the near surface of the railhead. Another observation is the trace on top of the railhead left by train wheels along the train running direction. The trace indicates that mixed traffic conditions (with different wheel dimensions) might have been running on the railway track. Mixed traffic types increase the complexity of interactions between wheel and rail (IHHA 2001). Metallurgical investigation on the rail sample was conducted. The results are shown in the next section.

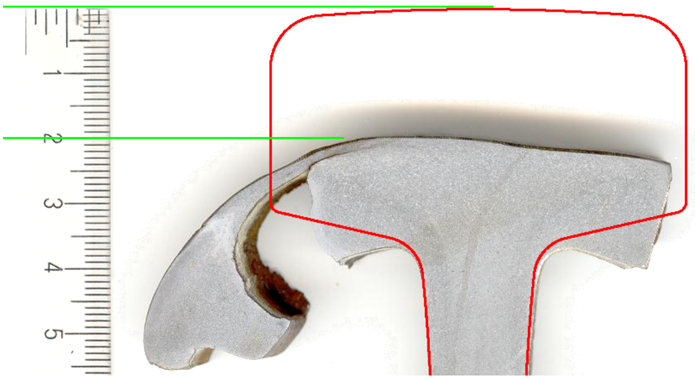

Figure 2. Comparison between the deformed rail head and an undeformed rail

METALLURGICAL INVESTIGATION

Chemical Composition

The chemical composition of the rail material was analysed using the optical emission spectroscopy (OES) method. Results are listed in Table 1 together with the compositions of BS11 normal grade rail (Garnham & Davis 2008) and 41kg rail (AS1085.1 2002). It can be seen that the carbon, silicon and sulphur levels of the rail sample are within the range of BS11 1959 rail specification, with Manganese being just outside the lower bound. Before 1980s, BS11 rails were commonly used in conventional railways with normal service conditions, such as the underground tracks in London Transportation system (Llewellyn 1998). To meet the requirements of high speed and heavy haul operations on railway tracks, many wear resistance and high strength rails have been developed by increasing carbon to around 0.8% to form a fully eutectoid microstructure, or by increasing other elements, such as 1%Cr (IHHA 2001).

Table 1. Predicted-to-test bond strength ratios: bond strength models

Element (w.t.%)	Rail Sample (This study)	BS11 1959 Normal grade	AS1085.1 - 2002
Carbon	0.45	0.40-0.50	0.53 to 0.69
Silicon	0.07	0.05-0.20	0.15 to 0.58
Manganese	0.78	0.95-1.25	0.6 to 0.95
Sulphur	0.02	0.060 max	0.025 max.
Phosphorus	0.07	-	0.025 max.
Cr	0.01	-	0.15 max.
Mo	<0.01	-	0.02 max.
Ni	0.03	-	0.10 max.
Cu	0.04	-	0.15 max
Al	<0.005	-	0.005 max.
V	<0.01	-	0.03 max
Ti	<0.01	-	0.025 max.
Sn	-	-	0.04 max.
Nb	<0.01	-	0.01 max.

Microstructure Examination

Four rail samples were prepared using a cutting machine with a low cutting speed. Coolant was used during the sectioning in order to minimize the heating of the samples. The samples were mounted using a two-part cold mounting resin system, and polished using aluminium oxide powder to a 0.3 µm finish. Polished samples were etched for 60 seconds in a Nital etchant, with 2% nitric acid and 98% methyl alcohol (Eden et al. 2005).

An Olympus BX40F4 optical microscope with 500x magnification was used for microscopy examination of the rail samples. Optical images were taken from samples at different locations with an increasing depths from the surface of the railhead. Figure 3 shows an image taken at 5mm below the rail surface. It can be seen from Figure 3 that clear pearlitic lamella microstructure is surround by proeutectoid ferrite. By contrast, severe plastic flow was observed near the railhead within about 2mm from the railhead surface. Grains in this region were severely distorted due to plastic flow in the lateral direction as shown in Figure 4 that was taken at a depth of 80 µm into the railhead. It can be seen that both proeutectoid ferrite and pearlite are severely deformed with grains being layered and reoriented along the lateral direction. The grains below the main crack are less deformed than the grains above the crack.

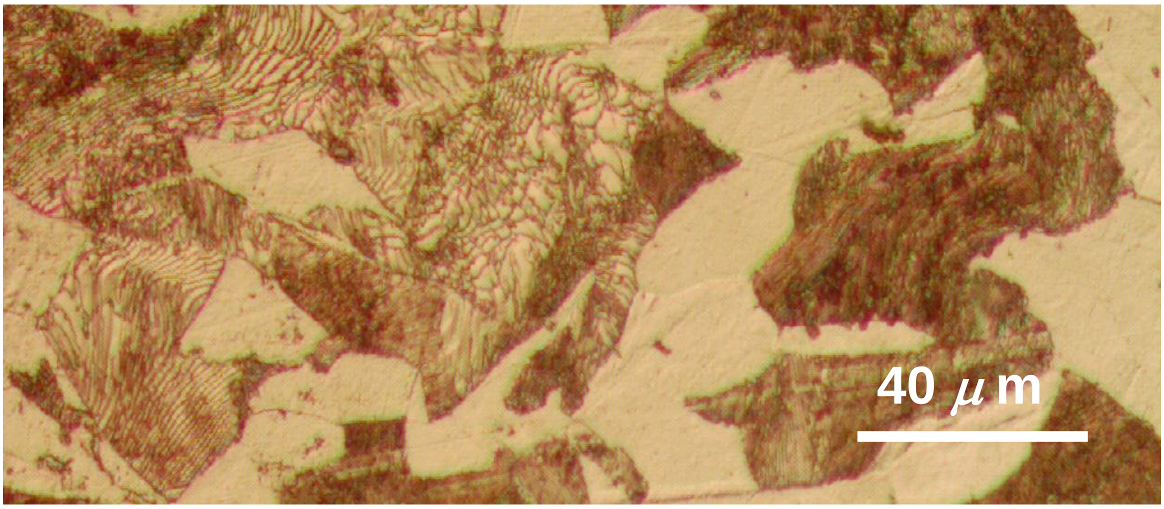

Figure 3. Pearlitic lamella structure with ferrite (light phase) and cementite (dark phase)

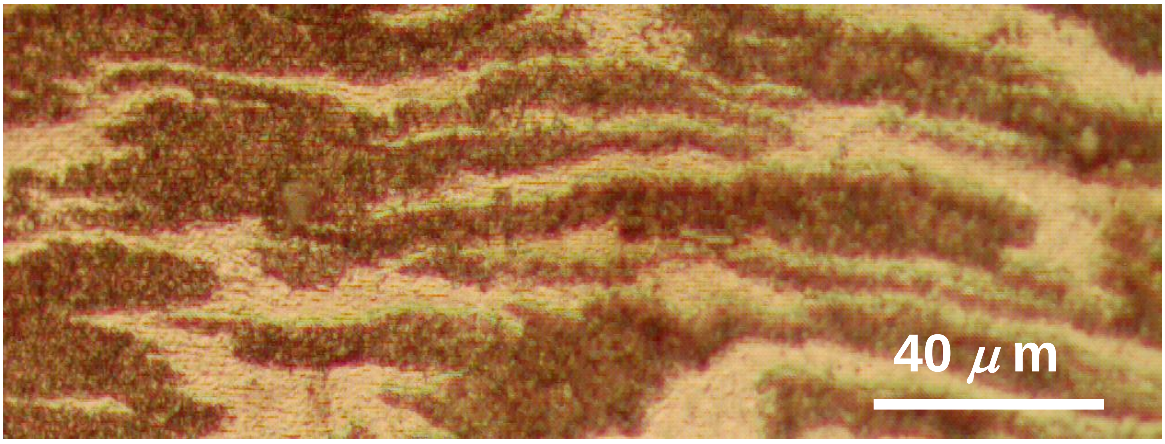

Figure 4. Heavily deformed proeutectoid ferrite and distorted pearlite structure (80 µm from the surface of the railhead)

Hardness Tests

Vickers hardness tests were conducted on the rail sample from the centre to the side and from the surface to the inside of the railhead in accordance with AS1817.1 (2003). The HV hardness results are shown in Figure 5. A test force of 5kg was applied and hold for 10 second. The average diagonal length of indentations was 182 µm. It can be seen that the hardness was higher near the rail surface with HV values ranging from 320 to 385 due to the strain hardening. Variations in hardness measurements in certain locations were recorded, which may be due to the difference of hardness in ferrite and pearlite grains. It was found that the depth of strain hardened layers was about 2 mm, in which the hardness was decreased to the bulk material hardness (Average 261HV).

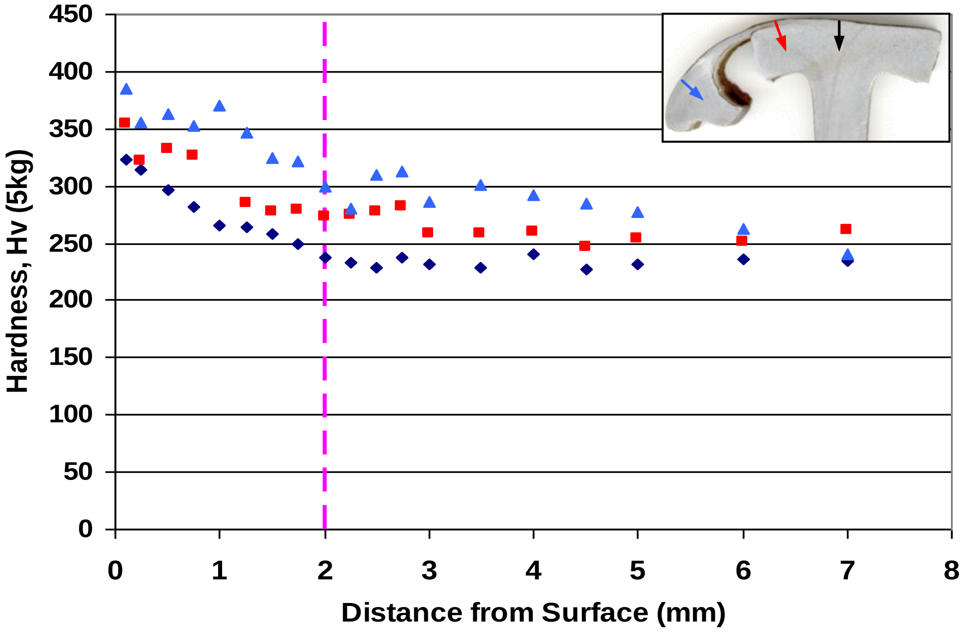

Figure 5. Hardness test results

DISCUSSIONS

Modern rail steel is classified as high carbon steel as it contains up to 0.8% carbon (Askeland & Phulé 2006). With less than 0.77% Carbon, BS11 normal grade rail was a hypoetectoid steel with ferrite as the primary microconstituent. Due to the continuous presence of primary ferrite, the steel was more ductile than steels with fully pearlitic microstructure.

British Steel carried out extensive laboratory wear tests on rail steels with different compositions and mechanical properties. Tests were conducted by rotating discs of railway wheel and rail materials under a controlled contact stress with a controlled amount of slip between the two discs. Wear was determined by weight loss on the rail test disc and expressed as mg/m of slip (Llewellyn 1998). The test results showed that BS11 normal grade rails experienced the highest rate of wear comparing with other wear resistance rails that were produced by increasing the carbon composition up to 0.8% to form fully pearlitic microstructure or by adding other elements, such as 1%Cr. The BS11 1959 and 1985 specifications for railway rails were replaced by BS EN 13674 2003 that makes many improvement in material compositions.

As a normal grade BS11 rail, the rail sample did not have the wear resistance properties required in material compositions, manufacturing techniques (heat treatments), microstructure refinement (fully pearlite) and improved hardness. Under mixed service conditions, such as various train speeds and axel loads, the rail steel was not suitable to be used in the designated curved section.

CONCLUSIONS

This paper investigated the metallurgical properties of a rail sample taken from a curved railway track. Through crystalline observations, chemical composition analysis and hardness tests, it was found the rail did not have the wear resistance properties required in material compositions, manufacturing techniques (heat treatments), microstructure refinement (fully pearlite) and improved hardness. Under various train speeds and axel loads, the rail failed by severe wear at the railhead. It is recommended a more sustainable rail steel be used for this curved rail segment. While microstructure and hardness examinations have been carried out in this study, one factor that is worthy of consideration in the future is the potential higher load on the low rail in the curved railway track.

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