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Fatigue failure of a flash butt welded rail

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Abstract

Medium carbon steel rails are commonly jointed by means of a flash butt welding procedure. To ensure an adequate service life for the structural component commonly subjected to fatigue loading, a rigorous quality control should be performed, both in welding parameters and in the surface quality of the welded joint. This work investigated the cause of a recurrent failure in a railway, with cracking always initiated in the rail in the region of the welded joint. All standard procedures of failure analysis were applied, with a careful assessment of the material characteristics and the fractured surface. It was concluded that fatigue cracks initiated near the weld bead and spread in a brittle mode, leading to premature fracture of the material. An in-depth analysis of the early cracks showed that the surface finishing of the weld bead was not appropriate, generating undesirable stress concentration. A recommendation to change the procedure of surface finishing of welded joint was held, aiming to decrease the number of accidents on the railway line.

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Keywords: Rails; Flash butt welding; cracking.

1. Introduction

In continental countries, logistics questions related mainly to the transport of high volumes for long distances must be accurately treated. The railway, according to Schneider (2005), is one of the most efficient and economical transport ways to attend this demand.

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The railway transport is an efficient transport way mainly if railroads have their integrity preserved during their service lives. Rails catastrophic failures during a train passage, may cause the train derailment, resulting in accidents with human lives and material goods losses (Aglan et al. 2011, Esveld et al. 2009, Zerbst et al. 2009, Rice 1994). Aiming to increase railroad service lifetimes, nowadays the manufacture of rails use modern steels with high mechanical strength and wear resistance. Moreover, due to the need to increase traffic, speed and axle load in the compositions, specific settings for the construction of railways have been employed. One example is the use of long welded rails in railway construction also continuously welded (Hämäläinen et al. 2008).

Structural deterioration phenomenon, which typically cause failure of modern rails, commonly involve strain control fatigue and are related with wagon wheels and rails mechanical interactions. Moreover, welded joints are microstructural discontinuities in railroads continuously welded and represent susceptible points for fatigue cracks nucleation and growth (Mansouri and Monshi 2004, Zerbst et al 2009, Hämäläinen et al. 2008).

This work investigated the cause of a recurrent failure in a flash butt welded joints of a high strength railroad.

2. Materials And Methods

Standard procedures for failure analysis were applied in this work. The analysis involved the following principal stages: visit to the rail welding plant, investigation about material's fabrication and use history, sampling procedures including the preservation of the fractured surface, macro and microfractographic analysis, chemical analysis, metallographic analysis, and mechanical tests (tensile test and hardness).

3. Results And Discussion

3.1. Welding Procedure

Main results from the visit to the welding plant are below presented:

- Before the welding procedure, rails have their edges cleaned by mechanical trimming (wire brushes) to remove oxidized layers and other impurities. They are then dried in a drying oven;
- Rails are welded by flash butt welding procedure and cooled in natural air;
- Welded joints present metallic burrs, due to the weld process, that are prominent despite being partially removed by shearing scissors;
- After cooling, grinding machine operators try to remove the excess of burr manually, but the process is not uniform and is inefficient.

3.2. Macrofractographic Analysis

Figure 1 presents the inferior part of the fracture surface of the rail, which was used in the macrofractographic analysis. It is possible to observe the fracture aspects at the head and at the web of rail. The rail web presents a region that reflects more intensely the light (flat and brightening). Figure 1 also shows that this flat region is localized at the internal side of the railroad, where train wheels exert higher effort over structure.

Figure 2 (a) presents a detail in the welded region. It is possible to observe three flat surfaces that reflect light more intensely. One of these flat surfaces, the biggest and central, highlights, because it has a curvature radius of almost one third of web rail thickness. This area characterizes the nucleation and stable crack growth. Radial marks are observed at right and left side of the welded joint. This is an evidence of crack instable growth (brittle fracture) in a long extension.

It is important to note that crack nucleation areas are localized at stress concentration regions: welded joint, sharp edges and grinding striations associated to the burr presences due to the welding procedure. These evidences, associated with a cyclic loading, which occurs in a normal operation routine of a railroad, leading to a final diagnosis of fatigue failure.

Figure 2 (b) presents pictures of rail parts (head, web and foot). In these areas is also possible to see radial marks, indicating that these parts were fractured by brittle mechanisms. It is supposed that fatigue crack grew until get a specific curvature radius (one third of rail web) considered the critical size and promoting a stress intensity factor correspondent to the material fracture toughness, causing a catastrophic failure at welded joint.

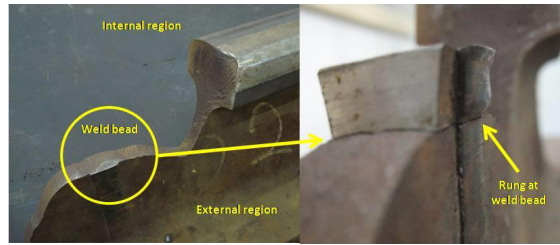


Fig. 1. Rail fracture surface, highlighting a rung at welded bead.

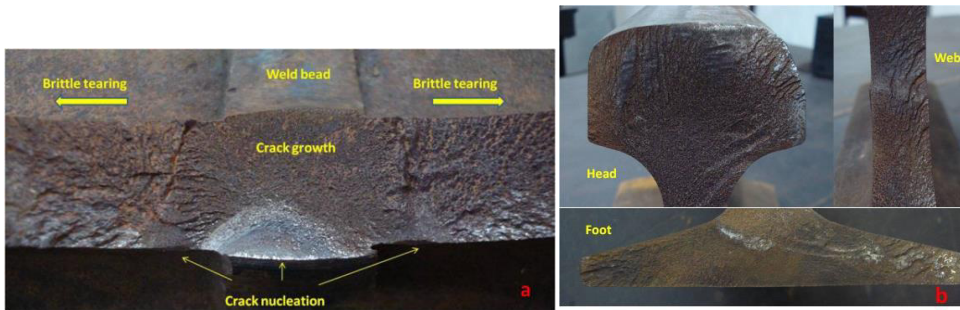


Fig. 2. (a) Detail of crack nucleation and stable growth regions (intense light reflection – flat surface). Brittle tearing areas (radial marks); (b) Head, web and foot presenting brittle fracture surfaces.

3.3 Chemical Analysis

The fractured rail was submitted to a chemical analysis by the optical emission spectrometry technique. The studied material is a hypereutectoid microalloyed steel. Carbon, vanadium and chrome contents are, respectively, 0.854%, 0.095% and 0.438%. This steel presented 0.781%, 0.846% and 0.014% of Si, Mn and P respectively. The expected microstructure for this steel is mainly constituted by pearlite.

3.4 Metallographic Analysis

As the crack nucleation occurred at the web of the rail, the selected and prepared surface for metallographic analysis was sampled in this area. Figure 3 presents the prepared and etched (Nital 2%) surface. It is possible to see the base metal (BM), the heat affected zone (HAZ) and the weld bead (WB). A central line (CL), revealed by its white contrast is also observed. Using this etched sample, it was possible to measure the distance between two HAZ zones. It is 35mm.

Figure 4 presents micrographs of BM regions etched with Nital 2%. As expected, the steel structure in base metal is constituted of pearlite. The coarser pearlite, the higher light reflection and the whiter constituent is. Fine pearlite (major fraction) has darker colors, because its colonies reflect less light.

Figure 5 presents micrographs of HAZ regions. These figures show the pearlite fragmentation (Iron carbide diffusion and cementite lamellae partially disintegrated) due to high heat input during welding process in this area.

Figure 6 shows micrographs of WB regions. In this area it is possible to observe that colonies of pearlite have higher sizes, indicating higher previous austenite grain sizes. In Figure 7 it is possible to see the central line. In this line, the microstructure is constituted of pearlite and proeutectoid ferrite. Ferrite grains are localized at pearlite colonies boundaries indicating local decarburization.

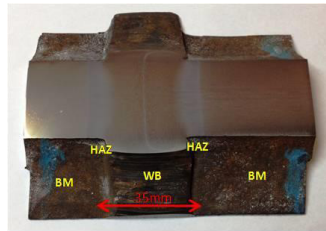


Fig. 3. Welded joint prepared for metallographic procedures. BM = Base metal; HAZ = Heat affected zone; WB = Weld bead; CL = Central Line.

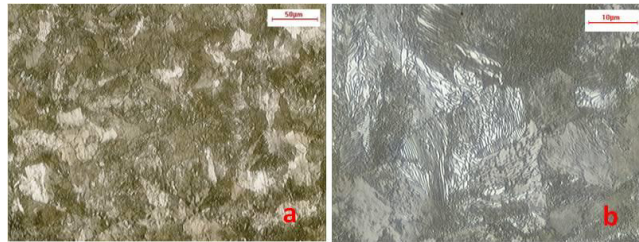


Fig. 4. Micrographs of BM; Nital 2%, OM. (a) 400X; (b) 2000X.

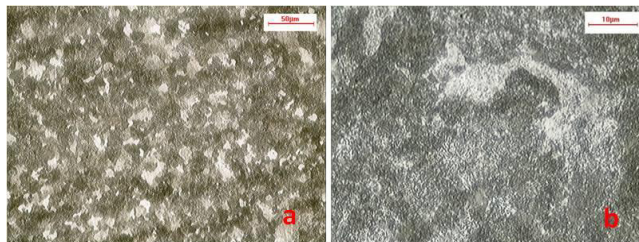


Fig. 5. Micrographs of HAZ; Nital 2%, OM. (a) 400X; (b) 2000X.

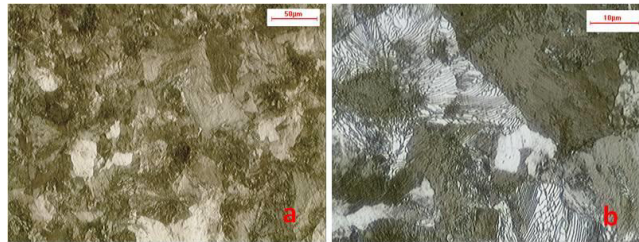


Fig. 6. Micrographs of WB; Nital 2%, OM. (a) 400X; (b) 2000X.

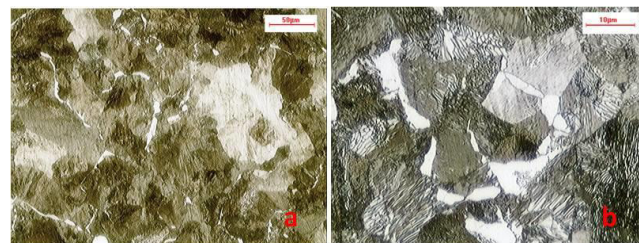


Fig. 7. Micrographs of CL; Nital 2%, OM. (a) 400X; (b) 2000X.

3.5. Mechanical Tests

The used sample in the microstructural characterization was submitted to Brinell hardness test ($F=187,5\text{kgf}$, $d=2,5\text{mm}$). Measures were done in BM, HAZ, and WB regions and CL. Figure 8 presents Brinell hardness profile measured in the failure welded joint. As expected, obtained values in BM and WB were similar, because both structures are pearlitic with small differences between colony sizes and interlamellar spacing. In CL, hardness values decrease slightly. This result may be explained due to proeutetoid ferrite presence in this area. In HAZ, hardness values presented a high decrease, justified by pearlite fragmentation verified in this region.

Tensile test specimens (ASTM E8M-09; $L_0=30\text{mm}$ and $d_0=6\text{mm}$) were sampled from rail head in two different positions: a set of specimens was sampled out from the welded bead (far from welded joint); other set was sampled in welded joint (welded bead in the middle of specimen). Table 1 presents the main mechanical properties of the studied steel measured in the tensile test for both conditions. It is possible to verify that yield (σ_{ys}) and tensile strength (σ_{ts}) of the specimens sampled in the WB region is lower than the measured for specimens sampled in the BM region, far from welded joint. Although the total strain (TS) for both configurations is similar, the area reduction (AR) is higher for the specimen sampled in the WB region.

Specimens sampled in the WB region presented highest AR and a recurrent failure out from the central part. Fractures happened recurrently at right or left extremity of specimens. Aiming to characterize these regions and understand recurrent fractures at the same place, welded samples were etched with Nital 2%. It was possible to observe that fracture systematically occurred at the HAZ region.

Table 1. Main tensile test properties.

Sample	σ_{ys} (MPa)	σ_{ts} (MPa)	TS (%)	AR (%)
In Welded Joint	977±18	1155±1	15±1	45±1
In Base Metal	1240±27	1463±13	17±1	34±5

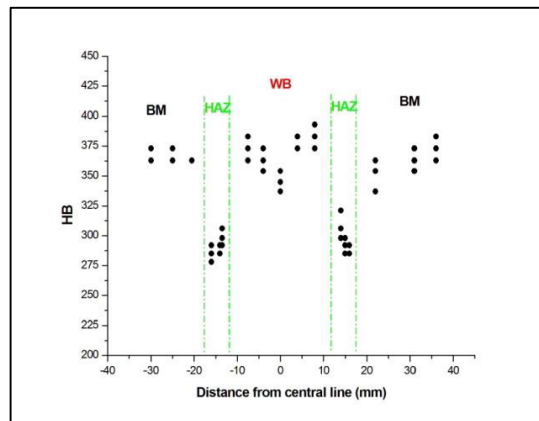


Fig. 8. Brinell hardness data. BM = base metal; HAZ = heat affected zone; WB = weld bead; central line (CL) at reference position 0.

3.6. Microfractographic Analysis

The microfractographic analysis was performed in a scanning electron microscope. In Figure 9(a) it is possible to confirm the phenomenon of fatigue as the main cause of crack nucleation and stable growth. Figure 9 (b) presents the transition area of stable to instable crack growth. Finally, in Figure 9 (c) it is possible to see cleavage facets and river marks, indicating a final brittle fracture caused by a tensile overload.

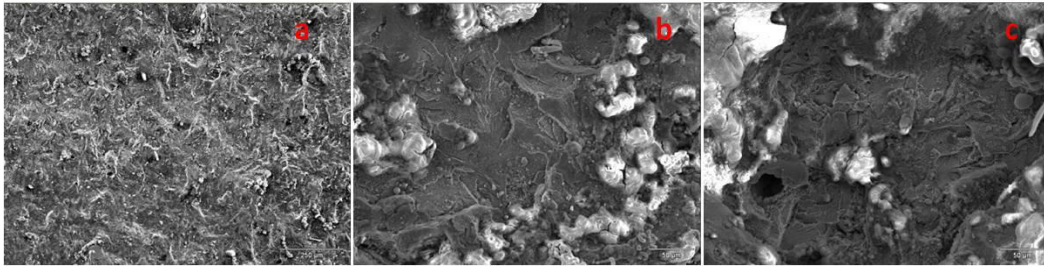


Fig. 9. (a) Start of fatigue crack spread (100X); (b) transition area (350X); (c) brittle fracture area (350X).

According to the results obtained, it is possible to affirm that the studied failure was caused by two mechanisms. First, a fatigue crack nucleated and grew steadily in the welded bead, specifically in internal parts of the rail web, where severe stress concentrators were observed (coarse burrs, grinding striations, sharp edges). Second, the fatigue crack grew, initially stably, until a critical size. As the material studied is a hipereutetoid microalloyed steel, with high mechanical strength and limited ductility, when it was subjected to specific overload levels, the existing crack grew unstably, until the catastrophic fracture of rail.

4. Conclusions and recommendations

The steel used in studied rail is a microalloyed hipereutetoid steel with carbon content of 0,85wt% and V and Cr contents, respectively, of 0,095% and 0,438%.

The welded joint presented a heterogeneous microstructure. The base metal and weld bead are constituted mainly by fine pearlite. The heat affected zone presents pearlite fragmentation and the start of cementite globalization. In the middle of welded joint, proeutetoid ferrite is present between pearlite colonies.

Mechanical tests indicated that the studied steel has high mechanical strength. The tensile tests in specimen sampled in welded bead presented a recurrent fracture in the heat affected zone, which had the lowest yield and tensile strength.

Crack nucleation occurred at the welded joint in a specific region where a rung is present at welding burr. The stress concentration effect was severe in the studied high strength steel, causing stable crack growth until one third of web thickness, from where it spreads unstably until the rail catastrophic failure.

Considering the flash butt welding procedure and its consequences on the rail welded joint (extremity of rails plastification, burr generation, grinding striations and other several stress concentrators), coupled to the work life of railroad under continuous fatigue cycles loading, some recommendations are suggested. Before welding procedures realization, rail extremities should be well cleaned, as the welding plant line. Undesirable dirt could contaminate the welding line causing the presence of impurities at metal welded structure; after welding procedures, rails should not be highly moved while they are in high temperature. Rails moving in high temperature may cause permanent strain at welded joint, creating another structural discontinuity; the dimensional and finishing control of welding burr must be urgently modified. More stringent criteria for burr removal and superficial finishing must be adopted aiming to decrease stress concentration points in welded joint.

References

- Aglan, H. A. Fatigue Crack Growth and Fracture Behavior of Bainitic Rails Steels. Federal Railroad Administration. EUA. 2011.
- Esveld, C. (2001) *apud* Zerbst, U; Lundén, R; Edel, K. -O; Smith R. A. Introduction to the Damage Tolerance Behaviour of Railway Rails – A Review. *Engineering Fracture Mechanics*, v. 76, 2009, p. 2563-2601.
- Hämäläinen, A-M; Salo, J; Martikainen, J. Flash Welding of Nonalloyed Welding Wire Steel. *Mechanika*, nº 6, v. 74, 2008, p. 63-68.
- Mansouri, H; Monshi, A. Microstructure and Residual Stress Variations in Weld Zone for Flash-Butt Welded Railroads. *Science and Technology of Welding and Joining*. v. 9, nº 3, 2004, p. 237-246.
- Rice, R. C. Shell and detail fracture formation in railroad rails. In: STEPHENS, R. I. (Ed). *Case Studies for Fatigue Education*, ASTM STP 1250, American Society for Testing and Materials, Philadelphia, 1994. p. 109-138.
- Schneider, E. L. *Análise da Vida Remanescente de Trilhos com Defeitos Transversais Desgastados em Serviço*. 2005. 115 folhas. Dissertação (Mestrado em Engenharia). Programa de Pós-Graduação em Engenharia de Minas, Metalúrgica e Materiais, UFRS, 2005.
- Zerbst, U; Lundén, R; Edel, K. -O; Smith, R. A. Introduction to the Damage Tolerance Behaviour of Railway Rails – A Review. *Engineering Fracture Mechanics*, v. 76, 2009, p. 2563-2601.
- Zerbst, U; Schödel, M; Heyder, R. Damage Tolerance Investigations on Rails. *Engineering Fracture Mechanics*, v. 76, 2009, p. 2637-2653.