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ASPECTS ABOUT THE RCF RAIL DEFECT CLASSIFIED AS SQUAT: A STATE OF THE ART

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Abstract. *The railway system is of great importance in the transportation of cargo and passengers around the world. The company VALE SA, in partnership with USP, UFPA and other Brazilian universities, is at the forefront of the Cátedra Roda-Trilho, a project where several aspects of this pair are studied. One frequent defect in rails, internationally studied, is the called Squat, which originated mainly by rolling contact fatigue (RCF). In this work, a state of the art on this defect is presented, where some aspects such as historic, location, appearance, detection and treatment of squat are discussed. Some research involving this one overtime is presented. The authors point out several mechanisms involving the initiation and propagation of the defect and in this work, a comprehensive synthesis is made of this.*

Keywords: *Rail defects, RCF, Squat, Rolling Contact Fatigue, Railway rail*

1. INTRODUCTION

The Railway System is composed of large infrastructure such as wagons, locomotives, rails, etc. Rails and wheels are one of the components most subject to failure, which can manifest as wear, defects and in the last case, fractures. Girsh et al (2009) affirm that the increasing demand for rail transportation around the world has been accompanied by increased axle load, higher train speed, and frequency of railroad use, which requires more carefulness with structural integrity to reduce rail failures and to increase the transport availability.

The rail is divided into three main parts:

The head that presents the contact with the wheel, the narrowest region linking the head to the foot, called web, and the foot that is the base of the rail (Figure 1a).

Rail is a structure that often suffers from fatigue. The rolling contact fatigue - RCF is the formation of cracks in the railhead surface, on the repeated rolling / sliding action between two metallic surfaces, in this case, the wheel and the rail (Carrol, 2005). RCF defects can be classified into two categories: subsurface and superficial defects (D173, 1990), as shown in Fig. 1b.

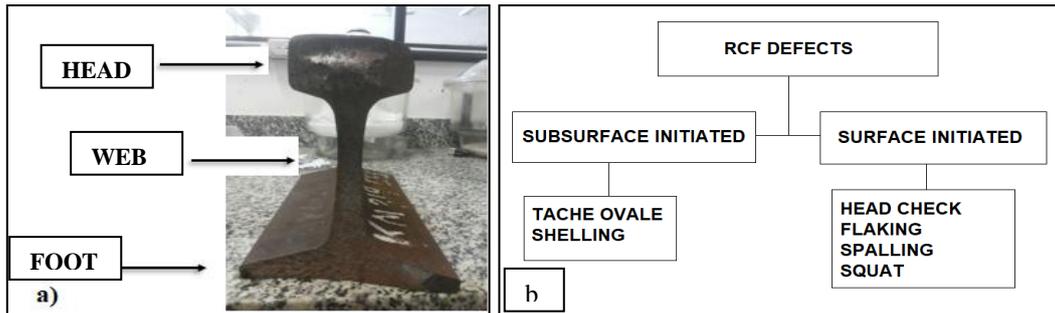


Figure 1. a) Railway rail parts. Source: From the survey. b) RCF defects classification. Source: From the survey.

Subsurface initiated RCF defects can be subdivided into two categories: subsurface defects associated with manufacture defects, such as the inclusion of oxides or the presence of hydrogen (Carrol, 2005), also called oval taches or shellings and the subsurface defects called ratcheting, which arise in the form of cracks and are characterized by the unidirectional accumulation of severe plastic deformation in internal layers that line the eutectoid lamellae causing dissociation (Kapoor, 1994).

Surface initiated RCF defects are represented mainly by head checks occurring in the rail gauge corner and the squats occurring in the running surface (Steenbergen, 2017).

2. RAIL SQUAT

Squats are defects classified as superficial originated from rolling contact fatigue, or RCF (Steenbergen, 2012; Grassie, 2012). Its aspect is diversified, however in most cases cracks are seen in the region of the rail head. They appear on the running surface as branched (typically V or U) or unbranched cracks (Steenbergen, 2013) and a local darkening (sometimes called dark spot) around the cracks caused by the crushing of the cracked region (Zerbst, 2009). Fig. 2 shows an example of a squat with these characteristics.

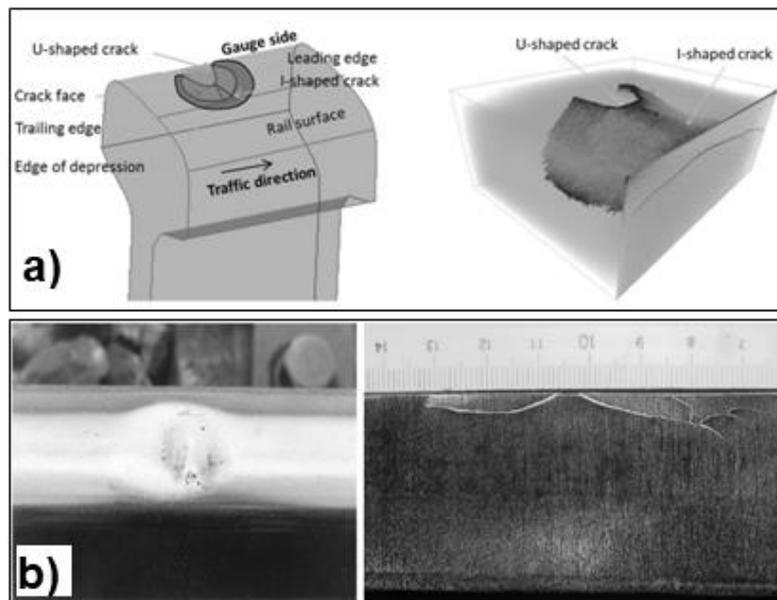


Figure 2. a) Schematic illustration of 3D squat crack and computed tomography. Adapted from Deng et al, 2018. b) Squat in the running surface, sharing the same aspects illustrated in a) and longitudinal cut of the same, showing cracks propagation. Source: Magel, 2011

The presence of squat depression on the rail surface increases the vertical dynamic load of the wheels on the track, which consequently accelerates the deterioration of the track and some components of the rail vehicle (Li 2011). In more severe stages, due to the continuous passage of vehicles over the crushed region, severe removal of material can occur, which is characterized as another type of superficial defect, called Spalling (Steenbergen, 2016). However, in these circumstances the wheel can also suffer serious degradation which, of course, tends to be passed on to the rail.

This defect requires attention for its immediate elimination or, if not, smoothing. Fig.3 shows an example of the drastic nature of the defect.

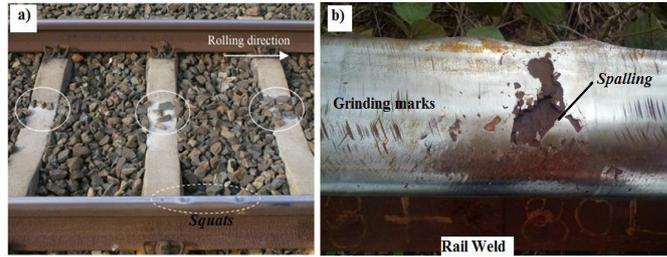


Figure 3 – a) Squats near to sleepers. Adapted from Zhao, 2008. b) Severe Spalling in Aluminothermic (Thermite) weld. Other irregularities can be seen next to the spalling. Source: From the survey.

3. HISTORICAL ASPECTS

Squats are one of the most frequent defects in international heavy haul railways and low/high speed (Ishida, 2013). The historic report squats since the 1950s on Japanese railways where they were named dark / black cracks due to darkening in the region. Also was called Rail Surface Shelling to differentiate from another defect known as Gauge Corner Shelling. The main difference between the two would be in the place of its origin. The term “Squat” appeared on the railways of the United Kingdom when it was reported (Ishida, 2013). Fig.4 illustrates a typical squat with dark spot presence.

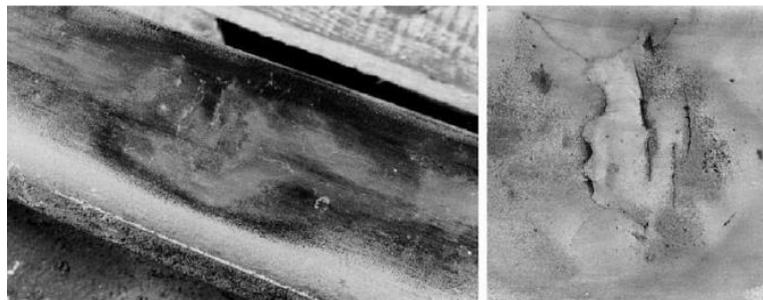


Figure 4. Dark spot and squat cracks on the running surface of the rail. Source: Zerst, 2009

4. CAUSES

There are several causes of squat: Indentations caused by hard objects on wheel/rail boundary, defects caused by wear and plastic deformation, corrugation, etc. Examination of the section of rails containing squats reveals that the cracks generated on the surface grow longitudinally and laterally at an angle between 10° and 30° relative to the running track, and then begin to transverse downward growth, as exemplified in Fig.5a and 5b. Other cracks return to the surface and may form other defects (li, 2009).

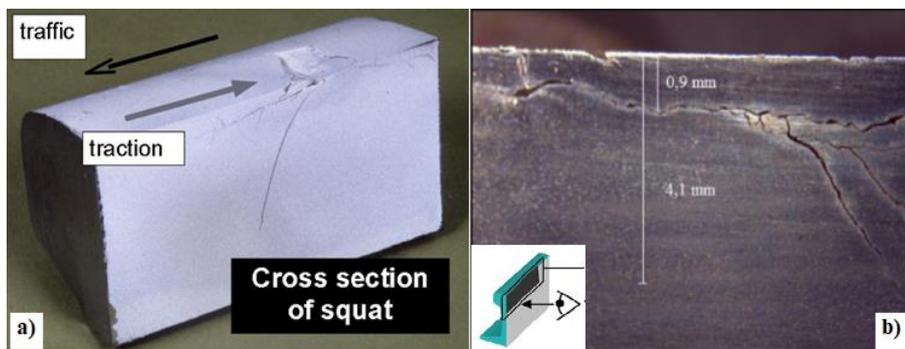


Figure 5. a) Aspect of squat cracks in rail head. Source: Railmeasurement.com. b) Longitudinal section of dark spot illustrating the subsurface propagation and branching of the cracks. Source: From the survey.

Squats can be originated from other defects like head checks and corrugations, however the mechanisms most commonly found is the white etching layer which in the literature is defined as a brittle layer and higher hardness than the base material of the rail. This brittle layer can initiate cracks that penetrate the material, propagating almost parallel to the surface and in the critical state these cracks change to the transverse plane causing the future catastrophic fracture of the rail (Ishida, 2013).

Welds represent discontinuity along the rail due to the variation of material properties such as strength, hardness and microstructure. Compared with typical aluminothermic (thermite) weld, the flash butt welding tends to produce narrower ZTA, as shown in Fig. 6a. It is important to understand the microstructural evolution and the phase transformation, particularly the spheroidization or divorced eutectoid, leading to the reduction of hardness in the ZTA during the welding process that causes canoamento (dipped weld) and squat defects (Fig. 6b). In addition, welded rails may contain burrs and high level of residual stresses. All these factors contribute to produce localized wheel impact, generating rail fatigue failures (Micenko, 2013).

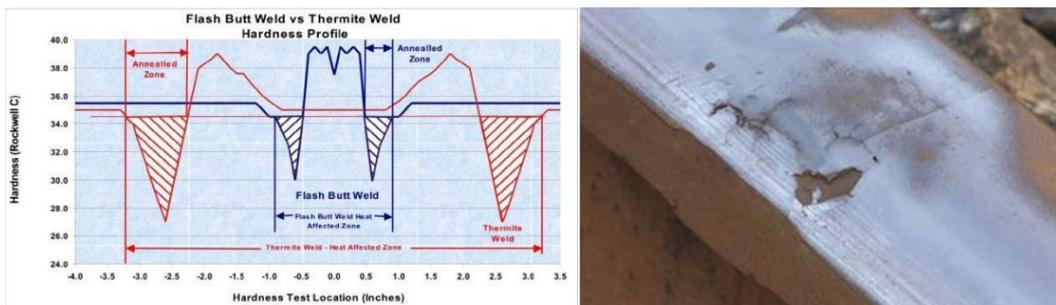


Figure 6 – a) Hardness profile comparison between flash butt and aluminothermic weld. Source: Micenko, 2013.
 b) Squat in aluminothermic weld. Source: Steenbergen, 2008

5. LOCALIZATION

According to (Zhao, 2012), this defect is more frequent in external rails of curves and on the sleepers. They are also found in tangent and smooth curve tracks (Pal et al, 2013). This is directly related to the wheel-rail dynamics and the stresses involved. In addition, studies carried out on Dutch railways showed the correlation between Squats and the characteristics of the other components of the track. Approximately 75% of registered Squats were found in the rail region over the sleepers. For example, if the analyzed track is divided into two parts, as shown in Fig. 7, about 74% of the squats occur in part I and the remainder in part II. In other words, 74% of the squats were found in the rail region over the sleepers (Li, 2009; Zhao, 2012). It is possible that this preference occurs by pure action / reaction phenomenon between the sleeper and the wheel / rail pair due to the absence of damping in part I well characteristic in part II.

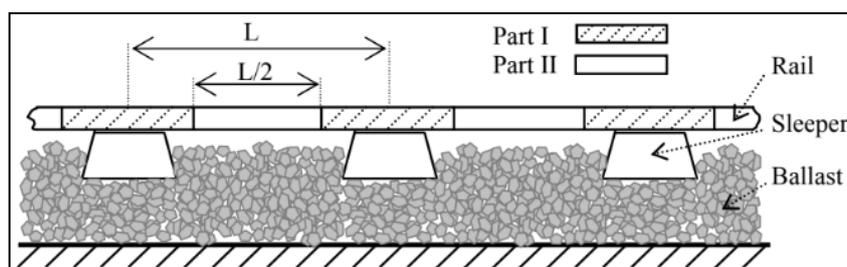


Figure 7- Definição de parte I e II. Fonte: Zhao, 2012.

6. DETECTION

Popovic et al (2013) presents some methods capable of detecting squats. The main method used nowadays is the ultrasonic (Steenbergen, 2016). The eddy current method is applicable for defects from 0.1 to 2.5 mm deep. The author recommends the combination of methods for detecting squats: visual inspection, optical system by cameras, ultrasonic inspection by ultrasonic cars and manual inspection by ultrasound and parasite currents every 6 months.

Due to the impact of the wheels during the passage over the squat, instrumented wheels can be used to detect the magnitude and frequency of impact forces caused not only by squats, but also other irregularities in the track.

7. TREATMENT

Repair and maintenance associated with squats and other defects has become costly on the railway infrastructure (Steenbergen, 2017). Grinding operations have been the main way to extend the useful life of the rail by removing RCF cracks and adjusting the rail profile (Satoh and Iwafuchi, 2008). Early detection of squats is extremely important as they can be removed by grinding (Popovic, 2013). Otherwise, if cracks are at depths greater than the level of the grinding, residual cracks may remain and require constant monitoring because they are very dangerous, requiring complete track replacement if the crack growth occurs (Al-Juboori, 2019).

8. SOME RESEARCH INVOLVING SQUATS

Several studies on this defect have been made in recent decades from various points of view. A few results were obtained that contributed to the understanding of the mechanisms involved.

Bogdanski et al. (2008) investigated the fracture and mechanism of fluid/water entrapment in squat cracks and stress intensity calculations using fracture mechanics. Fig. 8 shows the crack modeling.

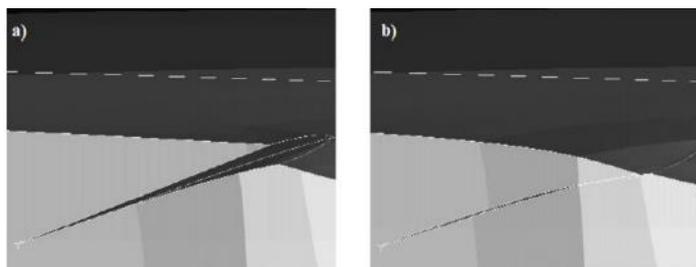


Figure 8. Modeling the crack to determine the volume of fluid trapped under the conditions a) open crack and b) closed crack. Source: Bogdanský, 2008

Simon et al. (2012) presented the tribological characterization of squats considering plastic deformation, microstructure and front of cracks. The defect is modeled three-dimensionally with the "saddle shape", as in Fig. 9.

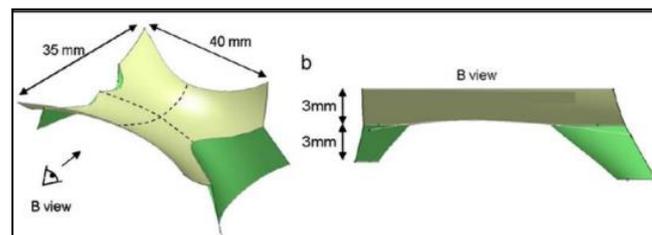


Figure 9. 3D Modeling of the Squat crack plane. Isometric and lateral view. Source: Simon et al, 2012

Peng and Jones (2013) presented modeling in Fig. 10, using finite element method (FEM) and non-destructive tests based on thermography to estimate squat size. This thermal evaluation uses infrared camera to detect the thermal waves and then produce the image of the defect. The experimental results showed that the finite element 3D model can be used to determine the squat location and crack depth.

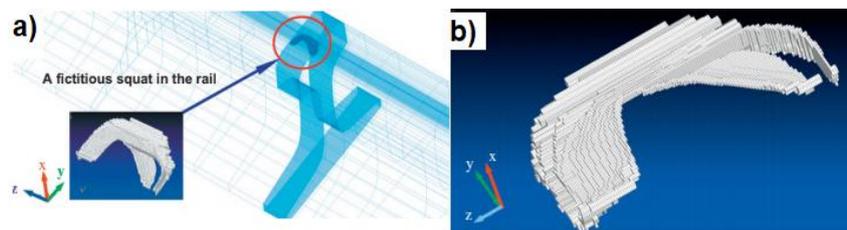


Figure 10. Model by finite elements of a) squat implanted in the rail head and b) three-dimensional aspect of squat cracks. Source: Peng and Jones, 2013

Steenbergen et al (2015) studied the squat formation from RCF that produce the leading crack (Fatigue propagation) and the subsequent development of the trailing crack by brittle failure mechanisms. Fig. 11 shows the schematic of the cracks and the propagation in the rolling and the opposite direction.

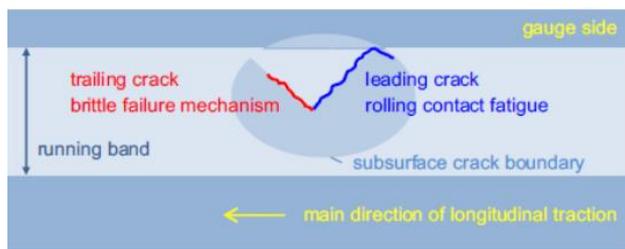


Figure 11. Schematic of the two squat cracks (Leading and Trailing crack) and their propagations. Source: Steenbergen, 2015.

More recent works such as Al-Juboori et al. (2019) presented an interesting fact that had already been noticed by several authors: The almost nonexistence of squats in tunnels, highlighting in this way the influence of water (mainly from rain) or other contaminating fluid in the degradation of the rail due to squat. The results showed that the rail tracks subjected to water influence showed deeper cracks reaching up to 7 mm deep, providing evidence regarding the theory of fluid entrapment (Fig.12).

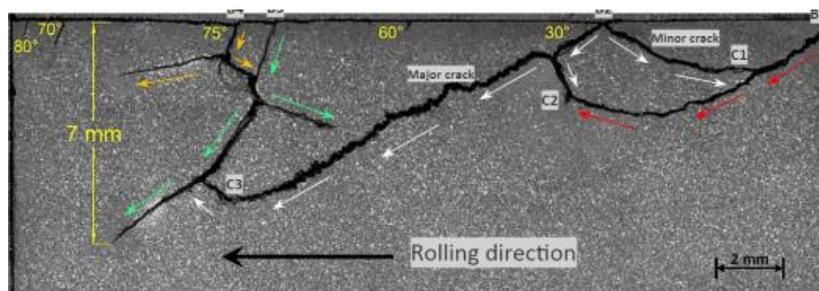


Figure 12. Longitudinal section of squat cracks, influenced by water, indicating 7mm maximum crack depth and crack angle. Source: Al-Juboori, 2019

9. CONCLUSIONS

From the comprehensive review of the state of the art of RCF squat defects, the complexity and the great international cooperation to understand and reduce the incidence of this defect is remarkable. Several researches have been carried out in the last decades on metallurgy, fracture mechanics, computational modeling, contact and working tensions with the objective of clarifying and tracing strategies for the treatment of the defect. The Grupo de Pesquisa em Engenharia de Materiais (GPEMAT) of the Universidade Federal do Pará (UFPA) in partnership with VALE S.A seeks the cataloging of this and other defects that are frequent in the rail component.

10. ACKNOWLEDGMENTS

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