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INSTITUTO FEDERAL Paraná

FRACTURE FAILURE ANALYSIS IN TIE RODS OF STACKER RECLAIMER

ANÁLISE DE FALHA POR FRATURA EM TIRANTE DE EMPILHADEIRA GIRATÓRIO (STACKER RECLAIMER)

Elton Lima de Sales[1]
Ully Guimarães Rocha[2]
Diego Moreira da Silva[3]
Sandro Rosa Correa[4]
André Rocha Pimenta[5]
Marilia Garcia Diniz[6]

Abstract: This work aimed to analyze the causes of premature failure by fracture of a tie rod of a large rotary forklift or Stacker Reclaimer. A methodology that included visual inspection techniques, macrographic analysis, optical microscopy (OM), Vickers microhardness (HV) measurements, scanning electron microscopy (SEM), semi-quantitative chemical scattering spectroscopy (EDS) and quantitative chemical analysis by optical emission spectrometry and combustion was employed. It could be concluded that the chemical composition of the material and / or the manufacturing process were outside the specification of the material due to the unexpected presence of magnesium and carbon graphite nodules, the latter considered to cause fragility that may have led the material to fracture by fatigue.

Keywords: Fatigue fracture failure. Stacker reclaimer. Graphite nodules.

Resumo: Este trabalho objetivou analisar as causas que acarretaram a falha prematura por fratura de um tirante de uma empilhadeira giratória de grande porte ou Stacker Reclaimer. Foi utilizada uma metodologia que incluiu técnicas de inspeção visual, análises macrográficas, microscopia óptica (MO), medidas de microdureza Vickers (HV), microscopia eletrônica de varredura (MEV), análise química semi-quantitativa por espectroscopia por dispersão de energia (EDS) e análise química quantitativa por espectrometria por emissão óptica e combustão. Pôde-se concluir que a composição química do material e / ou o processo de fabricação estavam fora da especificação do mesmo, devido às presenças indevidas de magnésio e de nódulos de carbono grafita, estes últimos considerados causadores de fragilidade que podem ter conduzido o material à fratura por fadiga.

Palavras-chave: Fratura por fadiga. Stacker reclaimer. Nódulos de grafita.

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[1]Mechanical Engineer, LACAM – UERJ, eltonsales91@gmail.com
[2] Mechanical Engineer, LACAM – UERJ, ullycp2@gmail.com
[3]Mechanical Engineer, LACAM – UERJ, diego-matias@hotmail.com
[4]Doctor of Materials Science and Metallurgy, CSN, sandro.correa@csn.com.br
[5]Doctor of Mechanical Engineer, LISComp IFRJ, andre.pimenta@ifrj.edu.br
[6]Doctor of Materials Science and Metallurgy, LACAM – UERJ, diniz@uerj.br

1 INTRODUCTION

Stacker Reclaimer is an equipment to recover and stack granulated solid materials. This equipment is used to control the inflow and outflow of materials, such as coal, cement, gravel and steel, determining, for example, the stock and volume of ore in mine yards or vessels (EXCELNEX, 2018; MAGNOR, 2018; VAN, et al., 2019). Such equipment may have an arm that exceeds 50 meters in length and, due to its large measures, it is necessary to be careful with the dimensional design of the components that support the operating loads (EXCELNEX, 2018). The Stacker Reclaimer analyzed in this work is of the rotary type, in which the rotating buckets collect material from the yard. This equipment is used when it is necessary to mix material classes, or for storage yards with limited space. In this case, they have an arm of up to 67 meters and staking rates of 6,000 tons per hour for coal, and up to 10,000 tons per hour for iron ore (GLOBALASSETS, 2018). Design mistakes, manufacturing problems, operation errors, or external impacts are often responsible for failures in equipment that work with high loads (BOSNJAK et al., 2011).

Tie rods are mechanical elements used for tensile loads only and, due to high slenderness ratio, these elements can buckle under compression loads (CARJUNKY, 2018). The loads applied on this mechanical element in the Stacker Reclaimer are very high due to the large amount of ore transported simultaneously. The loads applied to the machine structure and transferred to the tie rods are variable over time due to the intervals between the buckets during the rotation movement. Figure 1 shows a Stacker Reclaimer, the arrows show the tie rods anchor points, the places where fractures occurred in the case analyzed in this work.

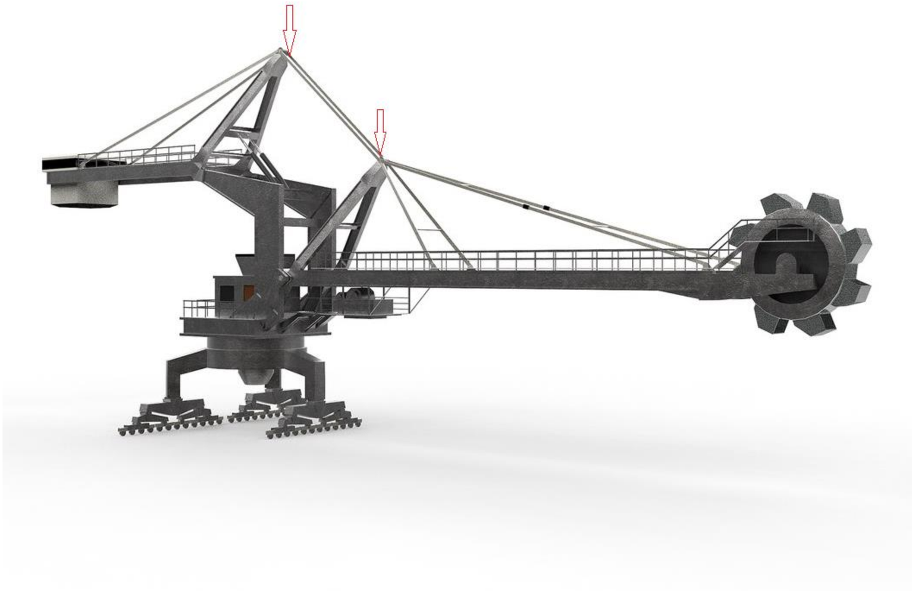

Figure 1 – Stacker Reclaimer, location of tie rods, arrows indicate the fracture site.

According to information from the company in which the equipment operated and design information, the tie rods are designed to have a minimum of 16 years of service life under normal operating conditions but they are changed every 8 years to avoid possible problems.

This work aimed to analyze the failure due to the fracture of tie rods of a Stacker Reclaimer used to recover and stack ore in the raw material yard of a large steel plant. The tie rods fractured with a duty time significantly shorter than eight years.

2 MATERIAL AND METHODS

Four samples of two tie rods that fractured in operation were delivered for analysis. All samples contained the preserved fracture surfaces, one of which was chosen to perform metallurgical analysis and mechanical tests. The sample of interest was 42 mm in diameter and 37 mm high (Figure 2).

Figure 2 – Sample chosen for analysis, where the tie fracture surface can be observed. The site of probable crack nucleation is indicated with arrows.

According to the datasheet of the equipment, the component should be made of AISI 1050 steel (carbon steel containing 0.5 C wt. %). Figure 2 illustrates Stacker Reclaimer tie rods design.

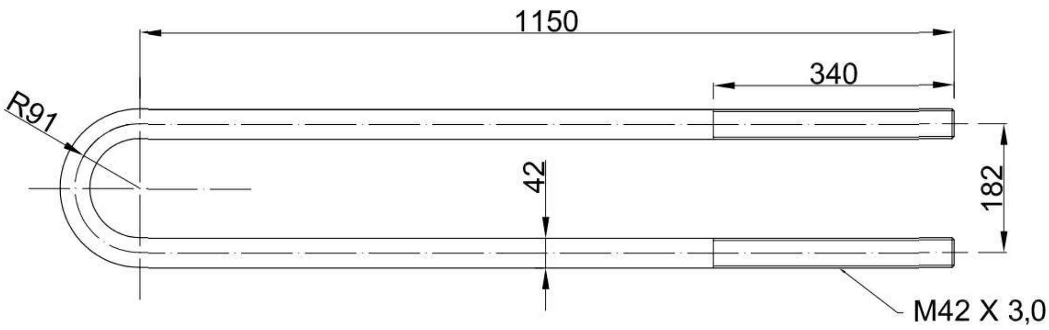

Figure 3 – Technical drawing of Stacker Reclaimer tie rods. Data provided by the company. Dimensions in mm. The fracture occurred on the threaded region, close to the interface of the unthreaded region.

After visual inspection and photographic recording of the fracture surface, small parts relatively distant from the fractured surface were removed for metallographic analysis. Two samples were cut, one in the cross section and the other in the longitudinal section. For this operation, a metallographic cutter model COR80/2 manufactured by Arotec was used. For optical microscope (OM) observation the samples were sanded, polished and etched with Nital 5% (5mL of nitric acid and 95mL of ethyl alcohol with analytical purity) for approximately 3 seconds.

The fractographic aspects in this work were analyzed using scanning electron microscope (SEM). The semi-quantitative chemical analysis were performed by the energy dispersive spectroscopy (EDS) technique, using a detector coupled in the SEM. EDS analyzes were performed with a minimum time of 100 seconds, to obtain measurements with greater accuracy (error of 0.3%). The SEM observations were taken on a JEOL JSM-6510LV microscope.

For the quantitative chemical analysis of the material, the optical spectrometry technique was used in a CX 9800 CREATE equipment. Vickers microhardness (HV) measurements were performed on the cross-section sample obtained close to the fracture region (ASTM, 2017). A microdurometer MV-1000A manufactured by PANTEC was used for this procedure. Ten measurements were made at random points on the sample, obtained with 200gf and 10 seconds of application.

Figure 4 – Cross section and longitudinal section of the fractured tie rods. Samples removed near the fractured region.

3 RESULTS AND DISCUSSION

Visual inspection of the fractured surface revealed oxidized regions, and the presence of grooves and unevenness, aspects typically associated with the Chevron patterns, recurring in failures due to the fatigue mechanism (SHACKELFORD, 2008). Figure 2 shows the fractured surface, where the marks are well in front of a small relatively flat region, supposedly the place where the crack nucleation process started and later spread (ASM HANDBOOK, 2002). The macroscopic aspect also showed that the probable place of the beginning of the failure was located in a machining groove in the threaded region of the tie rods. This region has a higher stress concentration due to the manufacturing process (BIASIBETTI, 2018).

The micrographic aspects obtained (Figure 5), showed that the microstructure of the material was in accordance with the specification for tie rods, i.e., a steel of type AISI 1050. All the regions analyzed presented a microstructure composed of grains of pearlite and ferrite (Figure 5(a) – pearlite are dark grains, and ferrite are light grains). The phases distribution is homogeneous and uniform, with ferrite being present in a smaller amount (ASM HANDBOOK, 2004). However, it was also observed the unexpected presence of numerous regions with an aspect typically associated with graphite nodules, which are surrounded by a carbon-depleted ferritic region (Figure 5(b)). Therefore, the microstructure of the material was not perfectly within specifications. Those nodules are typically present in nodular cast irons, and are associated with a combination of graphite alloying elements and cooling rates in the manufacturing process. The elements that favor the formation of graphite are silicon; cerium; and magnesium; however, steels of the type AISI 1050 do not have considerable percentages of those elements. The assumption of the presence of these elements was raised due to the graphite potential they have (OKAMOTO, et. al., 1984; SOINSKI, 2012).

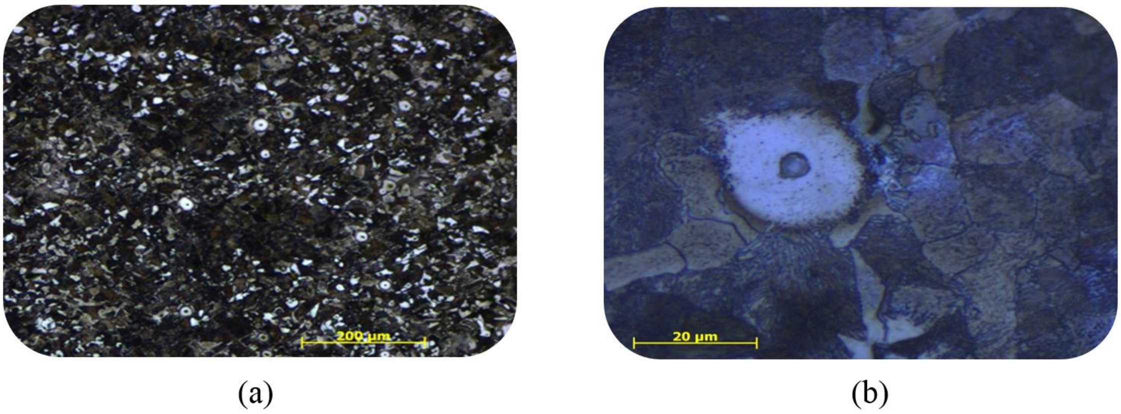

Figure 5 – Microstructural aspects obtained from the OM, Nital 5%. Region near the surface of the sample (a); and near of the center (b). Highlight for the graphite nodule surrounded by ferrite and the lamellar aspect of the pearlite.

The fractographies obtained in SEM did not allow obtaining information that characterized typical aspects of failure due to fatigue, both due to the oxidation present on the sample surface and due to high concentration of carbon nodules identified in several points of the fractured surface. The presence of nodules was already indicated by the micrographic aspects obtained from the OM and was confirmed by chemical analysis in the EDS technique. Figures 6 and 7 shows examples of the results obtained for the fractographic aspects and the spectrum of characteristic energies for several regions analyzed.

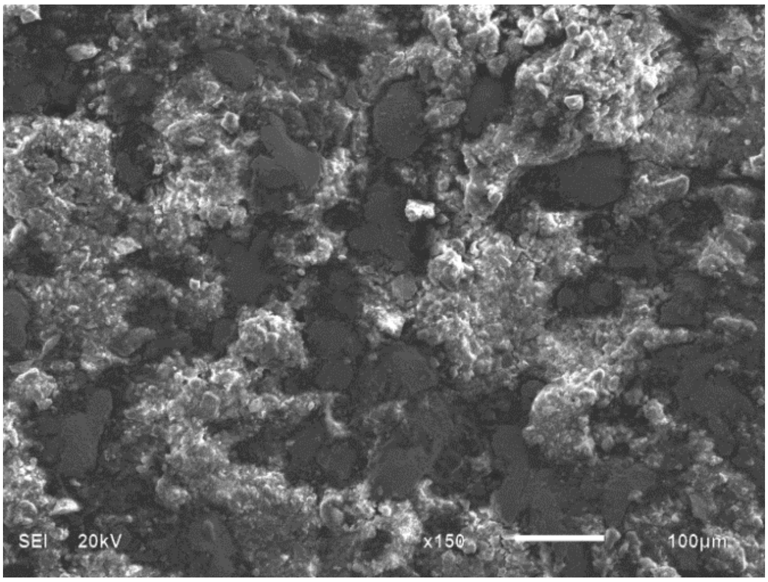

Figure 6 – Fractographic aspect obtained for all analyzed regions of the fractured surface. The darkest and most flat surface on the imagen are graphite nodules. SEM in secondary electron mode.

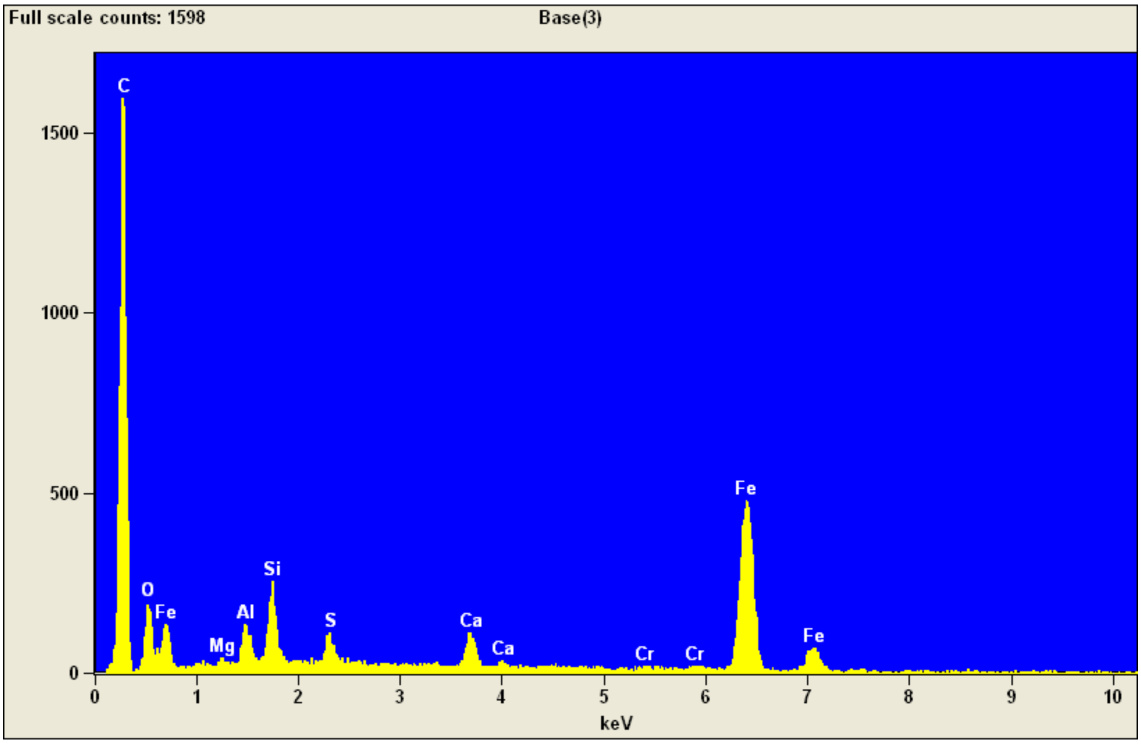

Figure 7 – Spectrum of characteristic energies obtained for several regions analyzed. Essentially the elements Fe, C, Si, Al and Cr were identified. The Ca element can be considered a contaminant on the surface.

Although carbon is difficult to identify by EDS, its high content allowed the confirmation of its presence at high peaks. In addition, the presence of a small magnesium concentration was observed. This presence was not expected for AISI 1050 steel and it could be responsible for the separation of carbon from the cementite and its coalescence, forming the graphite nodules (KIRBY, 1995; SOINSKI, et al., 2014).

To ensure that the result of the chemical analysis of the material was of good quality, the EDS signal capture lasted about 100 seconds per analyzed region. Thus, it was possible to detect about 0.16 wt. % of magnesium (Table 1).

Table 1 – Chemical analysis of the elements present in the fractured tie rods. The percentage values are relative and only indicate a ranking for the weight percentages present.

Element	**wt. %**
C	64.20
O	12.59
Mg	0.16
Al	0.91
Si	1.45
S	0.68
Ca	1.17
Cr	0.18
Fe	18.66
Total	100

A small sample of the fractured tie rods, taken from a location relatively distant from the fracture surface, was subjected to quantitative chemical analysis by optical emission spectrography and combustion techniques. The result is shown in Table 2.

Table 2 – Quantitative chemical analysis by optical emission spectrography and combustion techniques.

Element	**wt. %**
C	0.45
Mn	0.645
P	0.011
S	0.019
Si	0.152
Ni	0.047
Cr	0.073
Nb	0.002
Al	0.004
Mo	0.007
Ti	0.004
Mg	0.0127

Figure 8 exemplifies the distribution of chemical elements on the surface of the fractured sample through color images (EDS mapping). It is possible to observe that the regions with the presence of graphite nodules were essentially covered by iron, an element with greater atomic weight than carbon, and easier to detect than the latter.

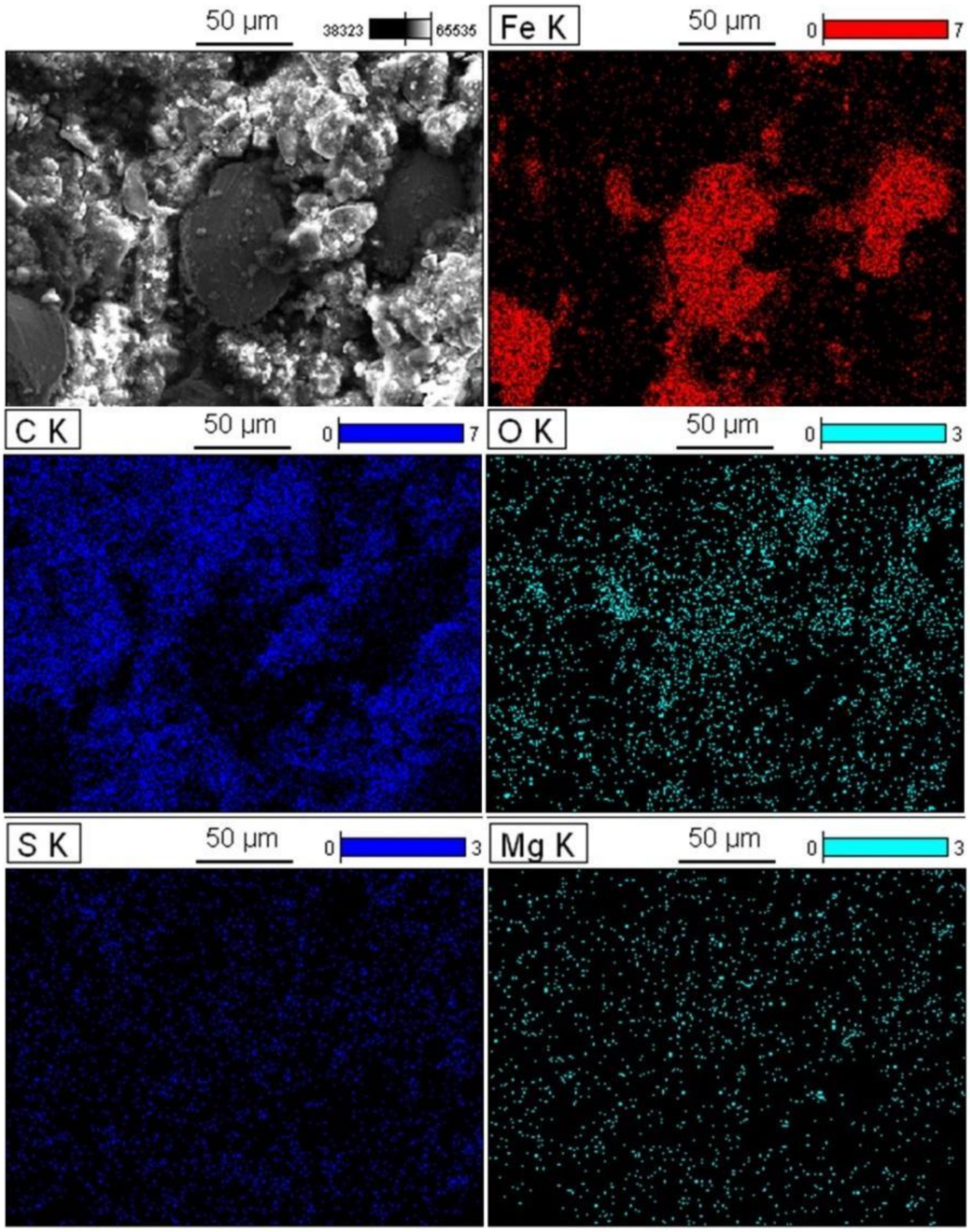

Figure 8 – EDS mapping analysis. The upper left image represents the region analyzed, the others the maps for each chemical element analyzed. The iron (red) was found to be abundant around the graphite nodules. Magnesium was evenly distributed, according to the lower image on the right.

For steel type AISI 1050, the presence of measurable levels of magnesium, silicon and chromium is unexpected. The Table 3 shows the typical chemical composition of steel type AISI 1050. The results of the quantitative chemical analysis corroborate the results by EDS, where the presence of the magnesium, an element with great graphitizing potential, was identified.

Table 3 – Chemical composition for steel type AISI 1050.

Element	wt. %
C	0.47 – 0.55
Fe	98.46 – 98.92
Mn	0.60 – 0.90
P	≤ 0.04
S	≤ 0.05

(MATWEB, 2018)

The percentage of carbon present (Table 2) is within the specified for the tie rods, as shown in Table 3.

The hardness found for the material was 196.54 ± 16 HV, which is in accordance with the hardness specified for AISI 1050 steels (198 HV) (MATWEB, 2018).

3 CONCLUSIONS

Through the employed characterization techniques, it was concluded that the fracture failure occurred, most probably, due to the significant presence of graphite nodules distributed throughout the material. The graphite nodules occurred due to errors in the chemical composition and/or in the manufacturing process of the steel. The graphite regions are fragile, particularly when associated with regions machined with threads, regions with different residual stress and stress concentration points. The results of the macroscopic analysis give evidence of a fragile fracture mechanism due to fatigue, although this has not been confirmed by fractographic observations on a microscopic scale.

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