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EFFECT OF MICROSTRUCTURE ON FRACTURE TOUGHNESS AND FATIGUE CRACK GROWTH RESISTANCE OF PEARLITIC STEELS FOR RAILROAD APPLICATION

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Abstract.
Two different types of eutectoid steels are used in the Brazilian construction of railroads. Premium and Standard types of rails are classified depending on the presence of certain alloying elements and the heat treatment done on the rails head. This work characterizes the microstructure and determines the fracture toughness and the fatigue behavior of five of those steels (four Premium and one Standard), coming from different countries. The microstructure was evaluated by light optical and scanning electron microscopy (SEM). Pearlite colony size (d) and pearlite interlamelar spacing (λ) were measured. In addition, tensile tests, fracture toughness tests (linear elastic fracture mechanics - K_{IC}), and fatigue crack propagation tests (da/dN x ΔK) were performed. The fracture surfaces of the specimens of all tests were analyzed by SEM to confirm the mechanism of fracture of the materials. Metallographic examination showed the presence of fine pearlite in all steels, with a normal distribution of inclusions, but with significant differences between the microstructural characteristics. Mechanical tests showed a significant difference among the steels. The microstructural aspects were correlated with the results of fracture mechanics and fatigue crack propagation in order to show the effect of the microstructure on the mechanical behavior of the steels. This information provides relevant information for an adequate selection of steel for railroad applications. It was confirmed that a more refined microstructure steels has greater tensile resistance, lower value of fracture toughness K_{IC} and worse behavior in fatigue, with smallest value of fatigue propagation resistance in crack growth region I (ΔK_{TH}). The fractography confirmed the brittle behavior of those materials.

Keywords: *Pearlitic Microstructure, Fracture Toughness, Fatigue Crack Growth Resistance, Railroad Steel.*

1. INTRODUCTION

The railway transport is an efficient transport way in continental countries (Schneider, 2005) 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, Zerbst *et al.* 2009, Zerbst *et al.* 2005, 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 phenomenons, which typically cause failure of modern rails, commonly involve stress and 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 susceptive points for fatigue cracks nucleation and growth (Mansouri and Monshi 2004, Hämäläinen *et al.* 2008, Zerbst *et al.* 2009).

The steels with pearlitic microstructure have been used in railway components due to their mechanical characteristics. In case of pearlitic steel, the pearlite colony size and the interlamellar spacing have important influence on the mechanical properties. Several studies about the effects of microstructural characteristics on the basic mechanical properties of pearlitic steels have been published. Gladman *et al.*, 1972, Hyzak, and Bernstein, 1976, and Dollar *et al.*, 1988 are classics contributions that show the influence of the pearlitic colonies size and interlamellar spacing on the yield strength of steel. Moreira *et al*., 2014 showed that rail pearlitic steels with different pearlite colony size and lamellar spacing have also different mechanical behavior.

The aim of this study is to characterize and evaluate the performance of Standard and Premium rails. The characterization of rail steels were done through microstructural analysis, strength, fracture toughness and fatigue crack propagation resistance. These tests were conducted in order to understand the behavior of the steels in the presence of defects, to develop comparative study of the performance between the five steels and to relate their structural characteristics with their mechanical properties.

2. MATERIALS AND EXPERIMENTAL PROCEDURES

2.1 Materials

Five steels manufactured for railroad applications were studied. The rails were identified as S, P1, P2, P3 and P4, where S is the Standard type of rail and P1, P2, P3 and P4 are the Premium type.

Table 1. Chemical composition of the steels (wt. %).

Steel	C	Mn	Si	P	S	Cr	Ni	Mo	V
S	0.722	1.240	0.539	0.01510	0.0047	0.218	0.0259	0.0166	0.0032
P1	0.792	0.880	0.304	0.01730	0.0043	0.209	0.0227	0.0166	0.0016
P2	0.863	0.910	0.261	0.01900	0.0091	0.218	0.0130	-	0.0010
P3	0.763	1.020	0.223	0.01600	0.0098	0.211	0.0180	-	0.0010
P4	0.754	0.807	0.687	0.01600	0.0068	0.319	0.0380	0.0010	0.0870

2.2 Experimental procedures

2.2.1 Microstructural analysis

The samples used for microstructure examination were cut, grounded, polished and etched with a 2% Nital solution. The samples were examined using a LEICA light optical microscope (LOM) and TESCAN VEGA3 scanning electron microscope (SEM).

The determination of the pearlite colony size was performed using a thermal etching technique in a furnace with controlled atmosphere. The atmosphere oxidizes, preferably, the boundaries of pearlite colonies. The samples were then analyzed by LOM, and the average colonies size was measured according to the intercept method, ASTM E112, 2014.

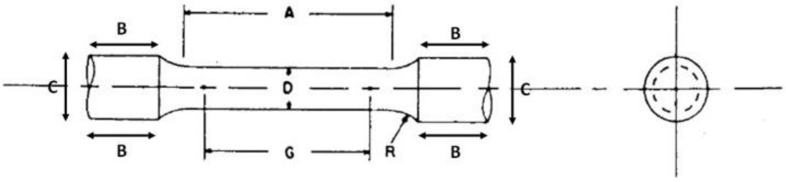
Silva, 1995, Gomes *et al*., 1997 and Limberger, 2000 claimed that by observing SEM micrographs is possible to measure the real interlamellar spacing by looking up the regions of smaller spacing, which will be the ones that the polishing plan will cut perpendicularly to the lamellar pearlite. The interlamelar spacing was obtained by Eq. (1)

$$\lambda=(VB.ML)/(MB.NL) \quad (1)$$

Where VB is the measure of the control bar (μm), MB is the real measure of the bar measured on the image (mm), ML is the length of the line drawn perpendicularly to the lamellae (mm) and NL is the number of cementite lamellae counted along the drawn line.

2.2.2 Tensile testing

The tensile test specimens were taken from the center of the rail head and were machined and tested in accordance with ASTM E8M, 2008. The dimensions of the specimens are shown in Figure 1.



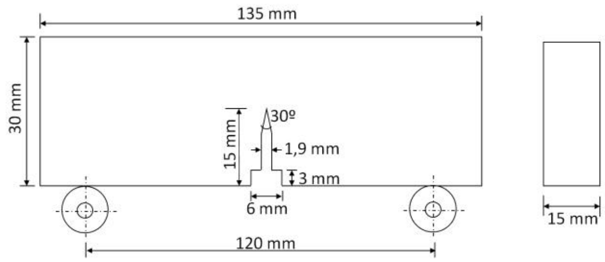
Parameter	Dimension (mm)
G	25
A	30
B	25
D	6
C	12
R	6

(a) (b)

Figure 1. (a) Tensile specimen drawing, and (b) is dimensions according to ASTM E8M, 2008.

2.2.3 Fracture toughness testing

The tests to determine the fracture toughness (K_{IC}) followed the recommendations of the standard ASTM E399, 2012. The SE(B) type of specimen was chosen and the specimens were taken from the railhead, in a way that the direction of crack propagation in the specimen would be the same that occurs on the rail in service (cross direction) (Limberger, 2000), as presented in Figure 2.



Thickness	B (mm)	15
High	W (mm)	30
Span	S (mm)	120
Pre-crack	a (mm)	16,5

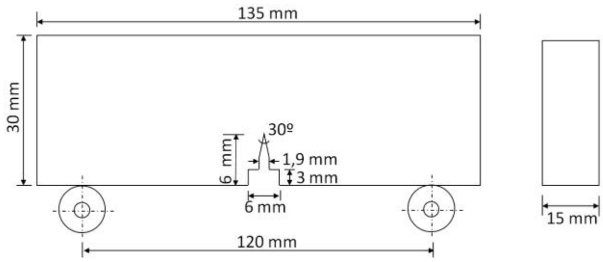
(a) (b)

Figure 2. (a) Schematic of the specimens used for fracture toughness testing and (b) their dimensions according to ASTM E399, 2012.

Three specimens of each steel were tested in the L-S direction. The notch of the specimens was oriented in the perpendicular direction of the railhead. This orientation is important because it represents the most dangerous crack propagation direction that could cause total separation of the rail. Before the test, as recommended by ASTM E399, 2012, a fatigue pre-crack was made. The tests were performed in a servo-hydraulic machine MTS810, in load control and a rate of 0.3kN/s, frequency of 30Hz and load ratio of R=0.1. The results were analyzed according to ASTM E399, 2012, for obtaining K_Q and validation of the K_{IC} test.

2.2.4 Fatigue crack propagation testing

The da/dN x ΔK curves were generated through fatigue testing according to ASTM E647, 2008, performed in two specimens SE(B). The standardized test specimens were taken from the railhead in a way that the direction of crack propagation in the specimen was the same direction of crack propagation in a rail service (cross direction), as shown in Figure 3. In this configuration, the crack tip was situated in a more homogeneous microstructure region with lower hardness, representing internal cracks. The fatigue tests were carried out after fatigue pre-cracking, at room temperature in L-S direction in a servo-hydraulic machine MTS810 with a frequency of 30Hz and load ratio of R=0.1.



Thickness	B (mm)	15
High	W (mm)	30
Span	S (mm)	120
Pre-crack	a (mm)	9

(a) (b)

Figure 3. (a) Schematic of the specimens for fatigue crack propagation testing and (b) their dimensions according to ASTM E647, 2008.

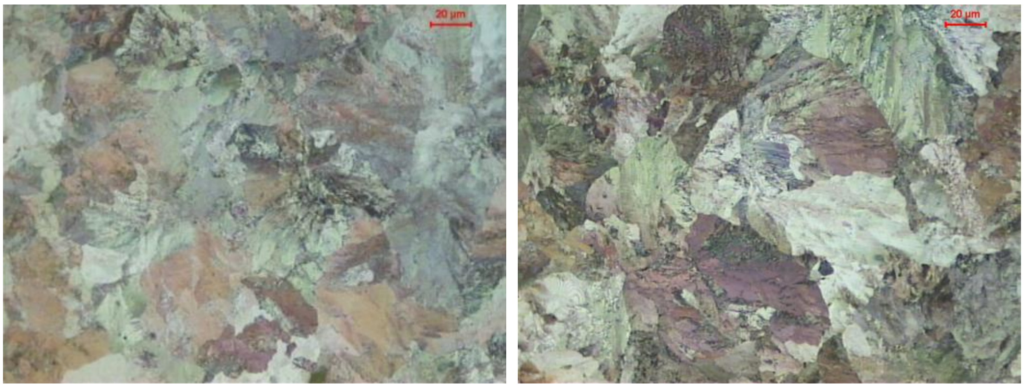
2.2.5 Fractography

The analysis of fracture surfaces were performed on specimens of all mechanics tests, via SEM, to identify and confirm the fracture mechanism of the steels.

3. RESULTS AND DISCUSSION

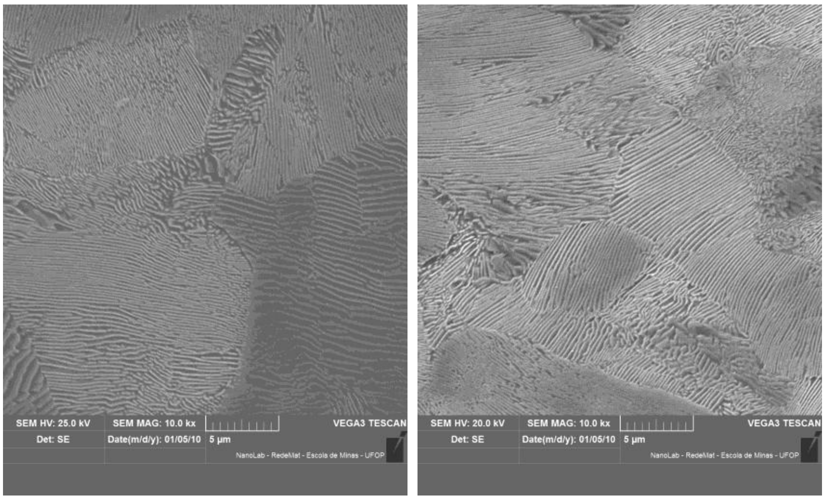
3.1 Microstructural analysis

Micrographs of the central region of the railheads are shown in Figures 4 and 5 for steels S (standard) and P1 (Premium). It was observed that all microstructures analyzed consisted of fine pearlite without the presence of pro-eutectoid ferrite. This microstructure was expected, since the chemical composition indicates eutectoid steels. Another important observed characteristic was the homogeneity of the microstructures.



(a) (b)

Figure 4. Micrographs of steels (a) S and (b) P1, LOM, 500X, 2% Nital etching.



(a) (b)

Figure 5. Micrographs of steels (a) S and (b) P1, SEM, 10000X, 2% Nital etching.

By following the procedure of intercepts (ASTM E112, 2012) it was possible to estimate the average grain size of all steels and the results are shown in Table 2. Steel S, which has the lowest carbon content, presented higher grain size; all Premium steels had very similar grain size.

Table 2. Average grain size.

Steel	**S**	**P1**	**P2**	**P3**	**P4**
d (µm)	43±3	32±4	35±4	38±4	28±3

The interlamellar spacing of pearlite was determined from the micrographs revealed via SEM. The results are shown in Table 3. Steel S showed the largest interlamellar spacing, confirming the effect of carbon on the microstructure.

Table 3. Interlamellar spacing.

Steel	**S**	**P1**	**P2**	**P3**	**P4**
λ (μm)	0.18±0.03	0.09±0.01	0.11±0.01	0.15±0.03	0.10±0.01

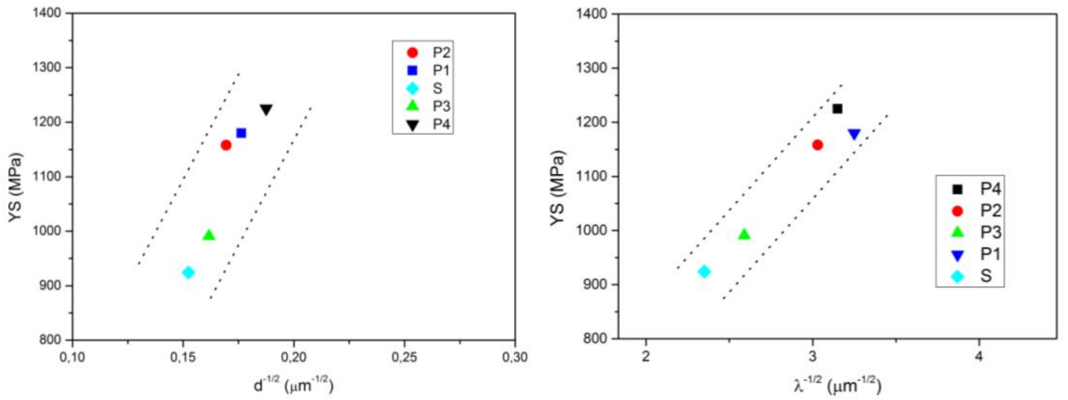
3.2 Tensile testing

The results from tensile tests, performed on three specimens for each rail studied, are presented in Table 4.

Table 4. Tensile test results.

Steel	**YS (MPa)**	**UTS (MPa)**	**ε_t (%)**	**AR (%)**
S	924±11	1056±4	9±3	18±2
P1	1180±72	1339±48	7±1	20±3
P2	1158±103	1277±62	7±2	20±3
P3	991±114	1249±40	10±1	27±3
P4	1225±65	1342±83	8	31

It is noticed that the rail P4 has the greater yield and tensile strengths when compared to the others, and the rail S is the least resistant. A more refined structure and higher carbon content provided the greater mechanical resistance, according to the literature (Gladman *et al.* 1972, Hyzak and Bernsteinm, 1976, and Dollar *et al.*, 1988). Figure 6(a,b) shows this dependence.



(a) (b)

Figure 6 - Relationship between yield stress - YS and (a) grain size - d and (b) interlamellar spacing - λ.

3.3 Fracture toughness testing

Table 5 shows the results of fracture toughness tests. The tests resulted on values for P_Q, P_{MAX} and K_Q that validate K_{IC} test, in accordance with ASTM E399, 2012. Those values of K_{IC} are in accordance with the values published in literature (Kavishe e Baker, 1985, Silva, 1995, Limberger, 2000, and Ravaee e Hassani, 2007) and are above the limit required by the European standard EN13574-1, 2003.

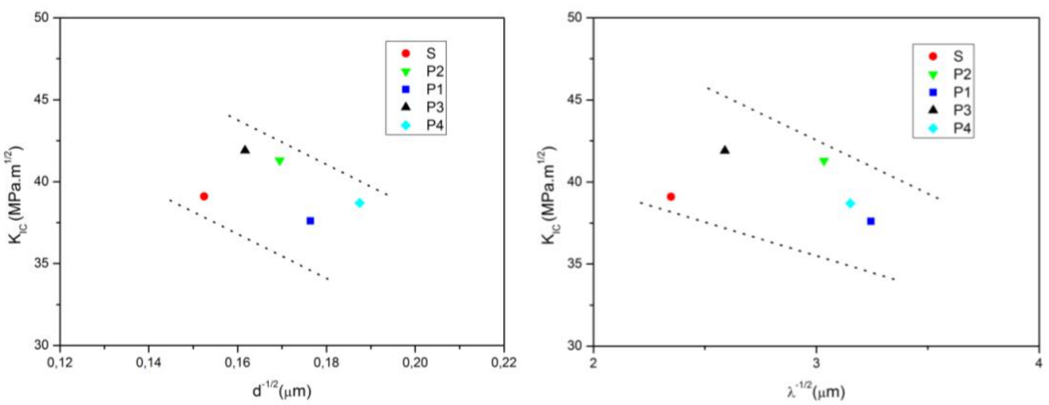
Table 5. Results of fracture toughness test (K_{IC}) for all steels.

Steel	**K_{IC} (MPa.m$^{1/2}$)**	**$B \geq 2.5(K_{IC}/YS)^2$ (mm)**	**$a \geq 2.5(K_{IC}/YS)^2$ (mm)**	**$P_{max}/P_Q \leq 1.10$**
S	39.1 ± 0.5	15 ≥ 4.5	16.5 ≥ 4.5	1.07 ≤ 1.10
P1	37.6 ± 0.5	15 ≥ 2.5	16.5 ≥ 2.5	1.07 ≤ 1.10
P2	41.9 ± 2.3	15 ≥ 4.5	16.5 ≥ 4.5	1.08 ≤ 1.10
P3	41.4 ± 1.3	15 ≥ 3.2	16.5 ≥ 3.2	1.05 ≤ 1.10
P4	38.7 ± 2.6	15 ≥ 2.5	16.5 ≥ 2.5	1.05 ≤ 1.10

Observing the relationship between P_{MAX} and P_Q and the results from tensile tests, it is noticed that the steels have similar and small ductility, despite the difference in strength.

The values of grain size and interlamellar spacing were compared with the fracture toughness values to verify the influence of the firsts on the second, as shown in Figure 7. The tensile yield stress and fracture toughness results were also correlated and are shown in Figure 8. The inverse trend between these two properties has been verified for many metallic materials.

Although there is little difference between the measured values of K_{IC}, steel rail P3 was the one with the highest value of fracture toughness, and among the Premium rails, P3 is the one with the largest values of grain size and interlamellar spacing, and lowest strength. These results are not consistent with the trend for several families of metallic materials: it would be expected an increased tensile mechanical resistance and simultaneous fracture toughness with the reduction of grain size and interlamellar spacing. On the other hand, Pickering, 1978, Kavishe and Baker, 1985 and Silva, 1995 showed that exists a relationship between the interlamellar spacing and the thickness of cementite lamellae, which must be considered to explain this behavior.



(a) (b)

Figure 7 - Relationship between fracture toughness - K_{IC} and (a) grain size - d and (b) interlamellar spacing - λ.

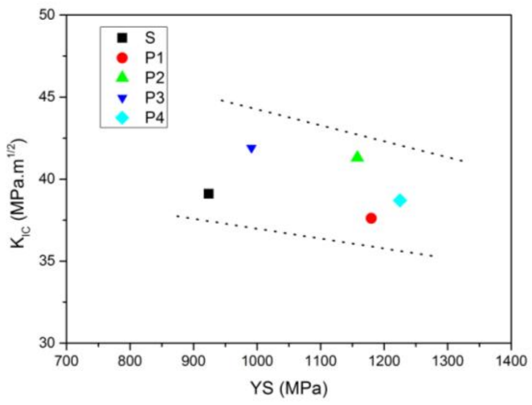


Figure 8. Relationship between the values of tensile yield stress and fracture toughness.

3.4 Fatigue crack propagation testing

The traditional sigmoidal curve of fatigue crack growth rate *da/dN* in function of the driving force *ΔK* is presented in Figure 9 as comparison among the steels. It is possible to observe a different behavior in regions I and III of crack growth (more sensitive to microstructure), and a similar behavior in region II. The different performance in the region I of fatigue crack growth is due to the variation in the crack closure (K_{CL}), as can be seen in Figure 10. This work found an inverse relationship between the fatigue threshold and the yield tensile stress of the steel, Figure 11, according to the literature (Cooke and Beevers, 1974, Romaniv *et al.*, 1983, Mutoh *et al.*, 2007). Thus, the microstructure which provides the best fatigue performance will not be the microstructure that ensures the best tensile resistance.

3.5 Fractography

The SEM images taken from the fracture surfaces of tensile, fracture toughness and fatigue crack propagation tests are exemplified by the result of S steel. All other steels showed the same behavior, Figures 12 and 13. The fracture surface analysis showed brittle behavior for all the steels.

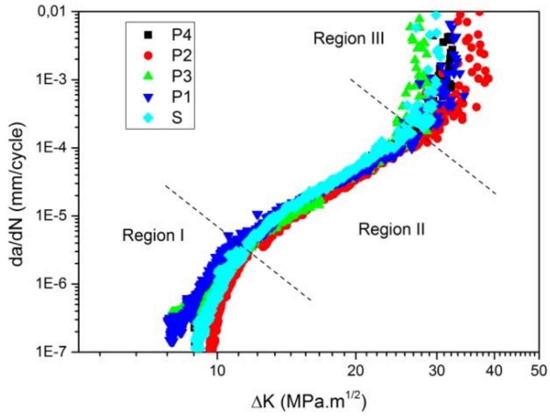


Figure 9. da/dN x ΔK curves of the five studied steels

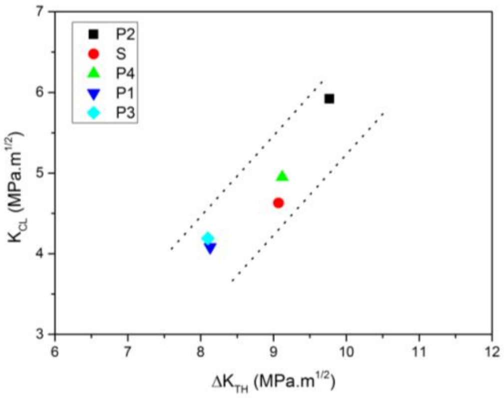


Figure 10: Influence of crack closure on the fatigue threshold of the steels.

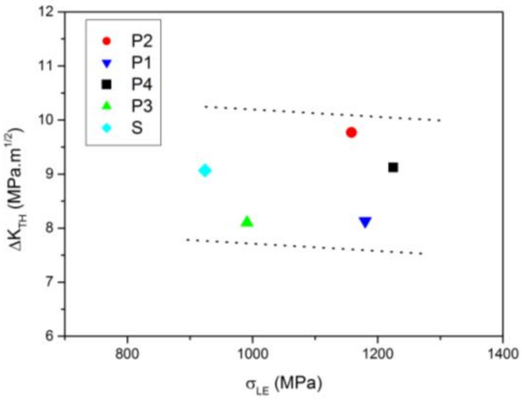
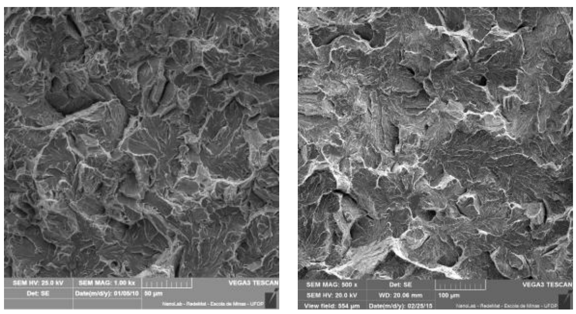
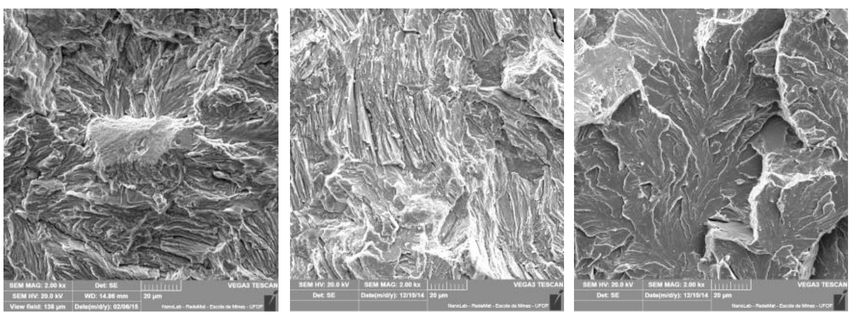


Figure 11: Yield tensile stress x fatigue threshold relationship.



(a) tensile test (b) fracture toughness test

Figure 12. Surface fractography, via SEM, of specimen from S steel.



(a) region I (b) region II (c) region III

Figure 13. Surface fractography, via SEM, of specimen from S steel.

4. CONCLUSIONS

The microstructures of the studied steels showed significant differences in the pearlite colony size and its interlamellar spacing. In this way, the mechanical properties studied had significant variation. The mechanical resistance is greater for a more refined microstructure, on the other hand the steels showed a worse behavior for a refined microstructure on fracture toughness and the fatigue crack propagation resistance. Therefore, it's very important an adequate selection of the steel for a particular purpose and location.

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