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EFFECT OF MICROALLOYING ON FATIGUE INITIATION AND CRACK GROWTH RESISTANCE OF A RAILROAD STEEL

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Abstract. *This research characterized the microstructure and evaluated the mechanical behavior of two pearlitic steels used in Brazilian railroads, a C-Mn-Si steel and a Nb-V-microalloyed steel. The microstructures were observed by light optical and scanning electron microscopy. Prior austenite grain size, pearlite colony size and pearlite interlamellar spacing were measured. Continuous cooling transformation diagrams for both steels were obtained. The mechanical behavior was evaluated by tensile tests, hardness tests, fracture toughness tests (linear elastic fracture mechanics - K_{IC}), and fatigue resistance tests: crack initiation tests (σ_a x N_f) and crack growth tests (da/dN x ΔK). The fatigue tests were performed with a load ratio R=0.1, at room temperature and frequency of 30Hz. The fracture surfaces of all tested specimens were analyzed by scanning electron microscopy. Hardness, yield and tensile strength, and fracture toughness were similar for both steels. The main difference in the mechanical behavior was verified in the fatigue crack growth tests: the fatigue resistance was higher for the microalloyed steel. These fatigue results are important to predict the actual behavior of steels used in the railway sector, to perform a proper maintenance control avoiding a premature failure and a consequent catastrophic accident, and to select the adequate material for this application.*

Keywords: *Fatigue crack tests, Microalloying, Railroad steel.*

1. INTRODUCTION

Brazil is a continental country, using an extensive railway network that crosses regions of significant geographic relief variation. The continuous increase of axle loads, frequency of trains and traffic speed cause a corresponding increase of stress and wear on the railroads over time, which can lead to nucleation and growth of cracks and structural deterioration of rails. Furthermore, by not producing rails nowadays, due to economic market limitations, Brazil imports steel rails from different countries, and sometimes the rail industry deals with steels that do not have a strict quality control (Godefroid et al., 2017, 2019). In this way, it is necessary to perform a rigorous microstructural and mechanical characterization of materials used in railways, to ensure better performance and avoid catastrophic failures with potential human lives and material loses.

Several studies (Cannon et al., 2003; Zerbst et al., 2005, 2009) about the mechanical behavior of rails have demonstrated that fatigue crack involving stress and/or strain control, is one of the major causes of failure that limit the rail life. More specifically, the fatigue crack initiating on the railhead that grows through its web and foot, as well as cracks from welded joints or from wheels/rails contact, are the most common modes of failure. The range of stresses imposed to the rails is generally not constant, hence the need to characterize the performance of the material as a function of the R ratio between loads and the behavior in face of overloads.

The rail steels are classified by the American AREMA Manual (2013) according to their chemical composition as standard or low alloy, and according to their hardness and tensile properties as standard, intermediate or high strength rail steels. For example, the minimum surface Brinell hardness (HB) required for low alloy steels is 310HB for the standard class, 325HB for the intermediate class and 370HB for high strength class. The corresponding European Standard (2003) on this subject also classifies steels used in rails from Brinell hardness ranges, adding minimum values for fracture toughness (K_{IC}) and fatigue crack initiation and growth resistance. There are no requirements for wear resistance.

Eutectoid fully pearlitic steels have been used in railway components due to their mechanical characteristics and relatively low manufacturing cost. The pearlitic microstructure is well suited for this particular application, which demands high tensile strength and wear resistance, combined with some ductility and fracture toughness. The pearlite microstructure is controlled by alloying and cooling rate. Rails may be head hardened by a supplemental cooling to increase wear resistance. Several studies about the effects of microstructural characteristics on the tensile mechanical properties and wear resistance of pearlitic steels have been published. Classic contributions show increasing yield strength and decreasing wear rate with decreasing of prior austenitic grain size, pearlite colonies size and interlamellar spacing (Gladman et al., 1972; Hyzak and Bernstein, 1976; Dollar et al., 1988; Clayton and Danks, 1990). While a significant number of investigations have focused on the strength, ductility and cleavage fracture stress of pearlitic steel, few of them discuss the fatigue behavior in general. Microstructure affects both the initiation and growth of fatigue cracks, but the microstructural conditions that increase the crack nucleation resistance are not necessarily beneficial to and in some cases are deleterious to fatigue crack growth resistance (Cooke and Beevers, 1974; Gray et al., 1983, 1985; Daeubler et al., 1990).

In a recent study, Godefroid and co-authors (2017, 2019) analyzed the mechanical behavior of some different pearlitic steels for application on railroads. The general idea of the study was to check the need to use microalloyed steels or if cheaper common steels (simpler chemical composition and microstructure, and a suitable thermomechanical treatment) could meet the required specifications for this application. This fact was confirmed, based on tensile, hardness, fracture toughness and fatigue properties.

Continuing with the research about steels for railroad application, the aim of the current study was to characterize the microstructure and evaluate the performance of other grades of pearlitic steels, always focusing on the railhead. One of the evaluated materials is a C-Mn-Si steel and the other a Nb-V-microalloyed steel. The characterization of steels was done by chemical composition and microstructural analysis (light optical microscopy - LOM, scanning electron microscopy - SEM). In addition, continuous cooling transformation (CCT) diagrams for both steels were obtained by dilatometry, to explain the possible microstructure differences, since knowledge of the phase transformation diagrams of these materials allows the choice for the best combination of chemical composition and cooling rates aiming to obtain a more refined pearlitic structure and an adequate surface heat treatment at the railhead. The performance of the steels was obtained by mechanical tests, including tensile, hardness, fracture toughness (K_{IC}), and fatigue tests (crack initiation = σ_a x N_f and crack growth = da/dN x ΔK).

2. MATERIALS AND METODOLOGY

Two eutectoid steels manufactured for railroad applications were studied. The rails were identified as CS (common steel) and MS (microalloyed steel with significant niobium and vanadium content: Nb + V ≈ 0.1%). The AREMA standard (2013) shows that the CS steel is standard, while the MS steel is a low alloy rail steel. In this work, the highlight is the presence of niobium and vanadium in MS steel, an important alloying element used as an agent that contributes to hardening mechanisms, such as grain size and precipitation, maintaining good fracture toughness.

The samples used for microstructural examination (pearlitic colony size - d and interlamellar spacing - λ) were cut, ground, polished and etched with 2% Nital solution. The samples were examined using a LEICA light optical microscope (LOM) and a TESCAN VEGA3 scanning electron microscope (SEM).

The dilatation of the samples as a function of temperature was determined using a L78 RITA - Linseis Messgeräte dilatometer at which type K thermocouples were spot welded on each specimen. The cylindrical specimens for dilatometry were 10.0mm in length and 3.0mm in diameter. Specimens were austenitized to 900ºC at a constant heating rate of 1ºC/s, maintained at this temperature for 60s and then controlled cooled with helium gas, applying eight different cooling rates. CCT curves were obtained with this methodology.

Specimens used for mechanical tests were obtained from the middle of the railheads in order to avoid top surface effects. This is especially important for the pearlitic railhead, which has undergone head hardening. All the mechanical tests were performed at room temperature in atmospheric air. Tensile tests (ASTM, 2016), fracture toughness (K_{IC}) tests (ASTM, 2017) and fatigue tests (ASTM, 2015a and 2015b) were conducted on a 100kN MTS servo-hydraulic materials testing system interfaced to a computer for machine control and data acquisition. The fatigue tests were performed with a load ratio R=0.1, at room temperature and frequency of 30Hz. The analysis of fracture surfaces by SEM was performed in all specimens after mechanical tests to identify and confirm the fracture mechanism of the steels.

3. RESULTS AND DISCUSSION

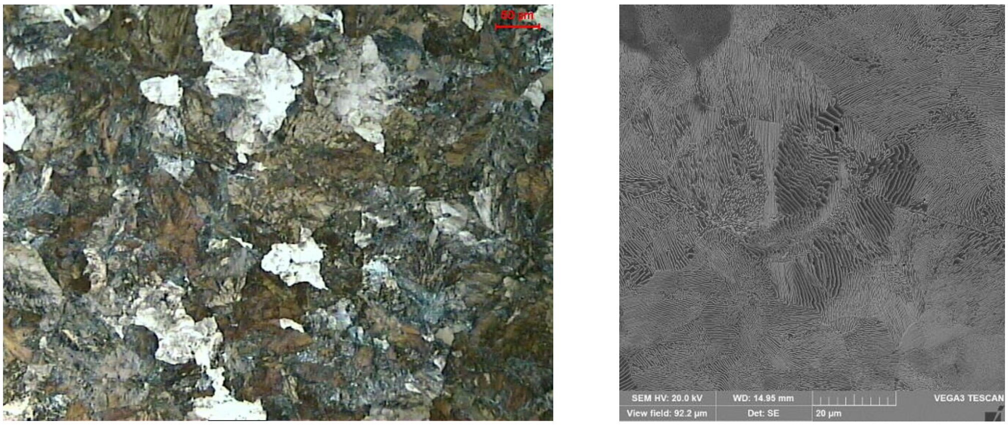
Table 1 shows the chemical composition of all studied steels. It should be noted that the two studied steels have completely pearlite microstructure when manufactured, even though they have different C contents. This can be explained by the contribution of two aspects: thermodynamic and kinetic. The thermodynamic aspect is associated to the additions of Si and Mn that move the eutectoid composition to values lower than 0.78. This, together with an out of equilibrium cooling, restricts the formation of primary ferrite, contributing to completely pearlitic microstructures.

Figures 1 and 2 show that the formed fine pearlite is different: the pearlite colony size and the pearlite interlamellar spacing is more refined values for the CS steel, indicating a different thermomechanical processing for the two steels. This is consistent because steels come from different manufacturers.

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

Steel	C	Mn	Si	P	S	Cu	Cr	Ni	Mo	Nb	V
CS	0.72	0.84	0.24	0.02	0.01	-	0.08	0.01	0.01	0.003	0.002
MS	0.77	1.04	0.47	0.01	0.02	0.01	0.01	0.01	-	0.03	0.06

(a) LOM. (b) SEM.
Figure 1. Micrograph of CS steel. 2% Nital etching. d = 17 ± 11μm; λ = 0.15 ± 0.02μm.



(a) LOM. (b) SEM.
Figure 2. Micrograph of MS steel. 2% Nital etching. d = 38 ± 4μm; λ = 0.24 ± 0.03μm.

The continuous cooling transformation diagram for the two studied steels showed that the CCT curves for the both steels are similar. Figure 3 shows this diagram. Although the chemical compositions are different, the thermal behavior of the two steels is then similar, indicating the possibility to have similar microstructures for a constant thermomechanical treatment.

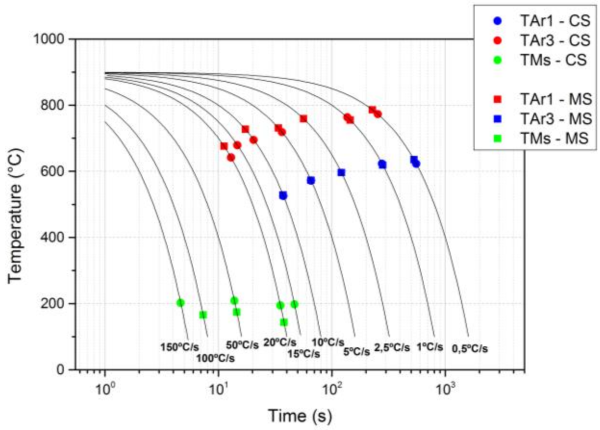


Figure 3. CCT diagram for the two studied steels.

It should be noted that at the austenitization temperature used in the dilatometry tests (900ºC), there is no significant dissolution of precipitates and, therefore, there is no significant fraction of Nb and V in solid solution in the austenite. Thus, these elements would not have a significant influence on the kinetics of austenite decomposition for the studied conditions, justifying the similarity of the CCT diagrams experimentally determined for the two steels. Considering this experimental evidence, and highlighting the microstructural differences of the steels in the as received condition, mainly in relation to the larger size of the pearlite colonies of the MS steel, it can be assumed that during the manufacture this one was probably austenitized at temperatures higher than of the CS steel, so that the beneficial effects of the microalloying elements could act during hot rolling and during accelerated cooling.

Figures 4 shows the hardness profiles between the surface and the interior from the railhead for both steels. Figure 5 shows the tensile curves of the two steels with fracture surfaces respectively shown in “Fig. 6” and “Fig. 7” shows a representative curve for the fracture toughness test of each steel, with fracture surfaces respectively shown in “Fig. 8”. Table 2 summarizes the main properties measured in these test: YS: Yield Strength; UTS: Ultimate Tensile Strength and DEF: Total Strain. The first important consideration is that both steels showed a hardness difference between the surface and the interior of the railhead, indicating a hardening treatment commonly used in rails steels for wear resistance. The mechanical tensile strength was slightly higher for CS steel than for MS steel, with a corresponding lower total strain, a behavior that is a consequence from differences of microstructural parameters between the steels. However, the difference is small, and it can be concluded that the microstructural changes were not able to influence significantly the mechanical behavior of the steels. The same conclusions can be drawn regarding fracture toughness. Both steel had a tensile semi-brittle behavior and a completely toughness brittle behavior. Nevertheless, the steels meet the AREMA (2013) requirements for railroad applications. Thus, it seems reasonable that the cheaper CS steel can be chosen for that application, and there is no need to concern about Nb and V microadditions. This conclusion was also recently found by Godefroid et al. (2017, 2019) with other pearlitic railroads steels.

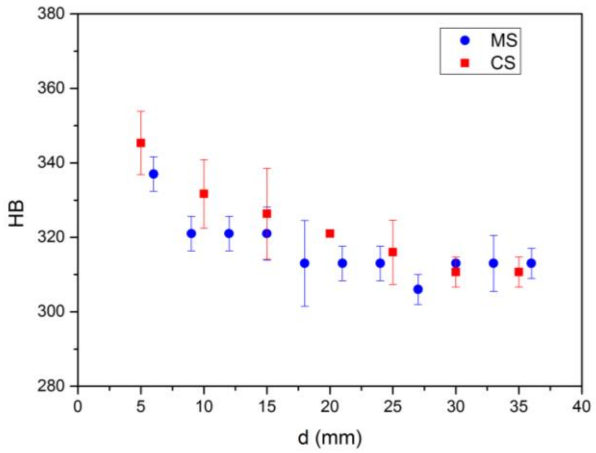


Figure 4. Microhardness profiles of the railhead for the two steels.

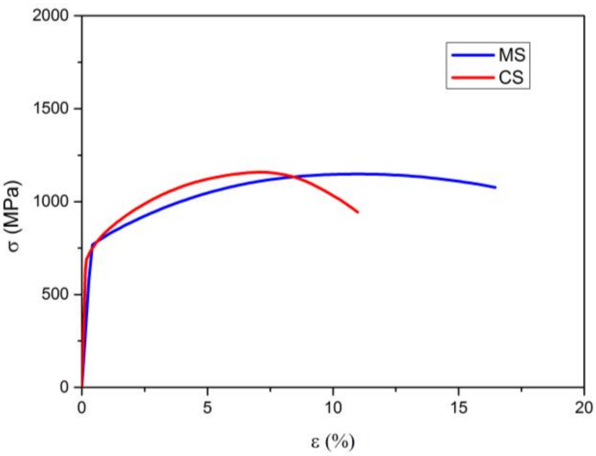
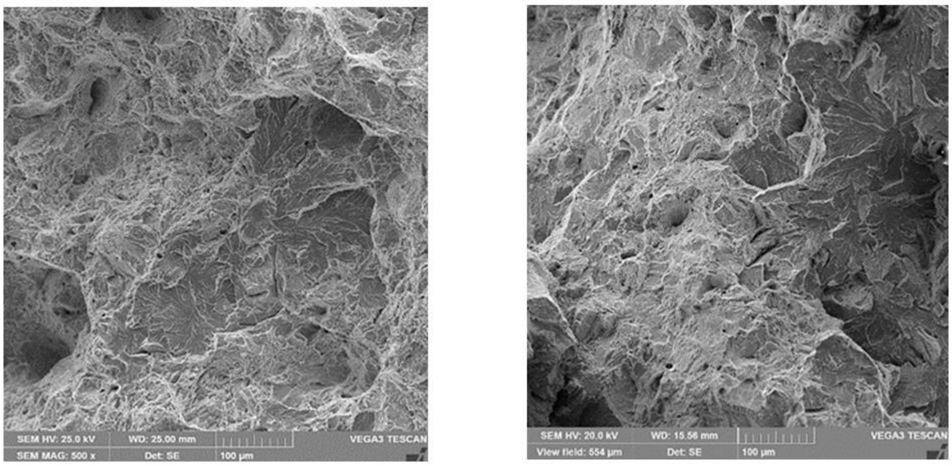
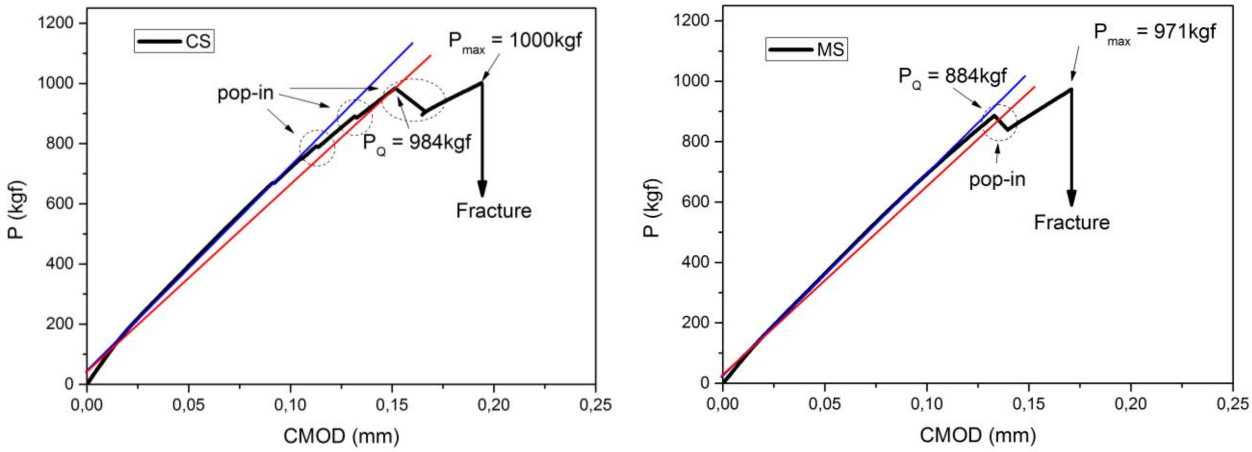


Figure 5. Tensile curves of the two steels.



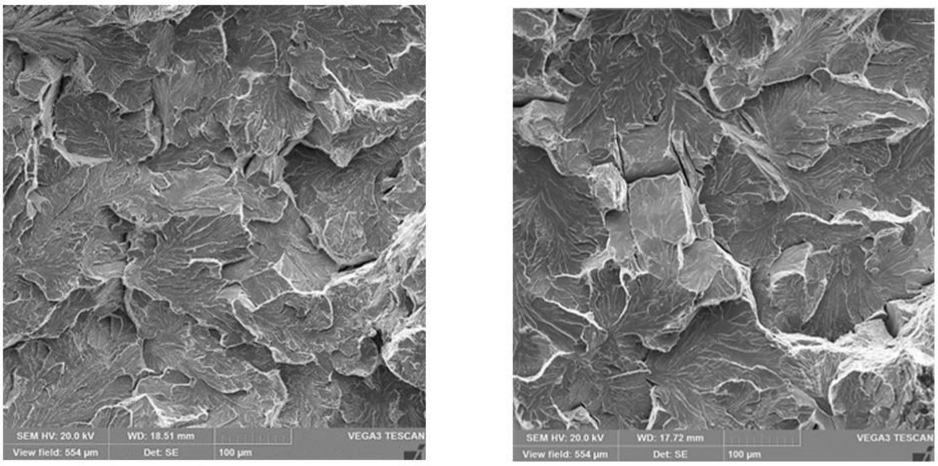
(a) CS steel. (b) MS steel.

Figure 6. Fracture surface at the center of specimens of representative tensile tests.



(a) CS steel. (b) MS steel.

Figure 7. Examples of load versus CMOD curves used to calculate the fracture toughness of the steels.



(a) CS steel. (b) MS steel.

Figure 8. Fracture surface immediately ahead the notch of specimens of representative fracture toughness tests.

Table 2. Mechanical tests result.

Steel	HB(1)	HB(2)	YS (MPa)	UTS (MPa)	DEF (%)	K_{IC} (MPa.m$^{1/2}$)
CS	347 ± 5	317 ± 1	769	1185	11	47 ± 2
MS	333 ± 6	313 ± 4	763	1149	16	45 ± 3

(1) meansured at 5mm below the surface
(2) meansured at 35mm below the surface

Regarding fatigue strength, two distinct situations must be considered: initiation and crack growth. On the one hand, there is a consensus in the literature that the crack initiation process generally occurs at the surface of the material as a consequence of cyclic slip and dislocations pile-ups. Initiation of fatigue cracks has been observed to occur along slip bands, at grain boundaries, at second-phase particles, and at inclusion-second phase interfaces, depending upon which occurs most easily. For pearlitic steels (Gray et al., 1985), it is observed that the main microstructural effect is the interlamellar spacing: refining the interlamellar spacing should reduce the pile-up stresses, thereby reducing the stress that could cause a cementite plate to fail, hence the increase in fatigue crack initiation resistance. In the case of the present work, “Fig. 9” shows that there was no significant difference in crack initiation resistance. This indicates that the microstructural changes were not sufficient to modify the behavior of the steels. This is another apparent indication for material selection in favor of CS steel over MS steel. The fracture mechanism was the same for the two steels, as can be seen in “Fig.10”, with the traditional initiation and propagation of crack from a surface region and brittle final tear.

On the other hand, “Fig. 11” shows that there was a significant difference in crack growth fatigue resistance in favor of MS steel. This difference is related to the crack closure phenomenon: for CS steel, K_{cl}/K_{max} = 0.25, while for MS steel K_{cl}/K_{max} = 0.35 (40% higher) at the threshold region. This indicates that for this part of the fatigue life the microstructural changes were sufficient to modify the behavior of the steels. The concept of roughness-induced crack closure is utilized by many researchers to explain the role of prior austenite grain size, pearlite colony size and pearlite interlamellar spacing on near-threshold fatigue crack propagation in fully pearlitic eutectoid steel. It is shown (Gray et al., 1983) that at low load ratios near-threshold growth rates are significantly reduced for coarse-grained microstructures, compared to fine-grained at constant yield strength, due to roughness-induced crack closure. Thus, being able to develop a microstructure capable of maintaining adequate tensile strength and fracture toughness, higher values for microstructural parameters are interesting for fatigue resistance. In this way, an adequate balance between the presence of microalloying elements and a thermomechanical treatment may lead to the development of a steel suitable for the desired application. It is important to consider that the AREMA standard (2013) does not specify criteria related to properties obtained from fatigue tests, making incomplete the procedure for materials selection for railroad applications. The SEM images taken from the fracture surfaces of fatigue tests are showed in “Fig. 12” and “Fig. 13”. For all steels the fracture surface presented a tortuous shape in region I (threshold), a planar form in region II (without striations), and brittle in region III (tearing of the material).

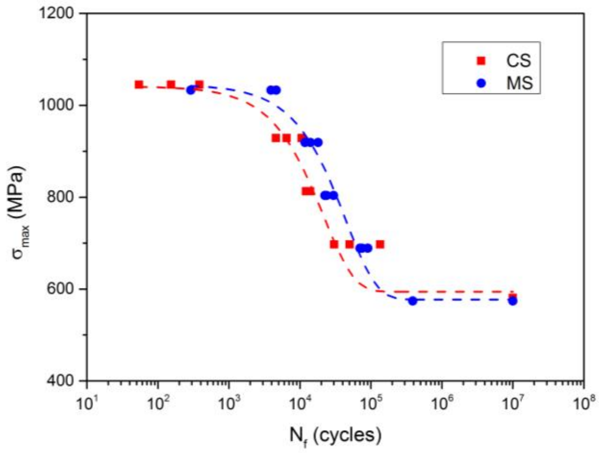
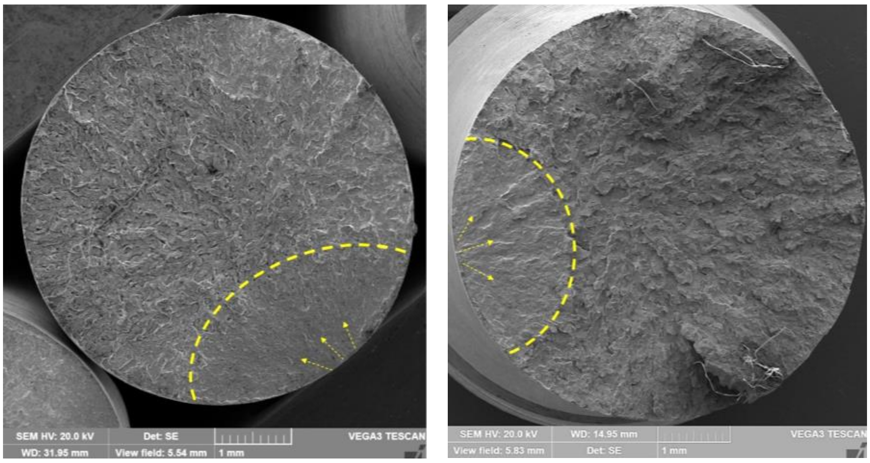


Figure 9. σ_a x N_f plot for the two steels.



(a) CS steel. (b) MS steel.

Figure 10. Fracture surface of specimens cyclically loaded at σ_{max} = 60%UTS. The dashed arc indicates the separation between the fatigue and tensile tear regions. The arrows indicate the crack nucleation and its growth direction.

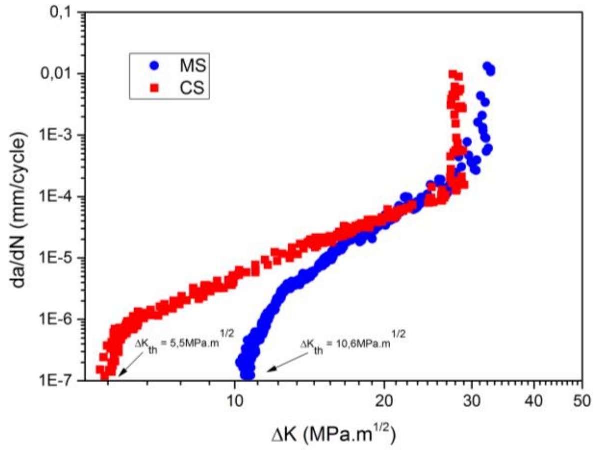
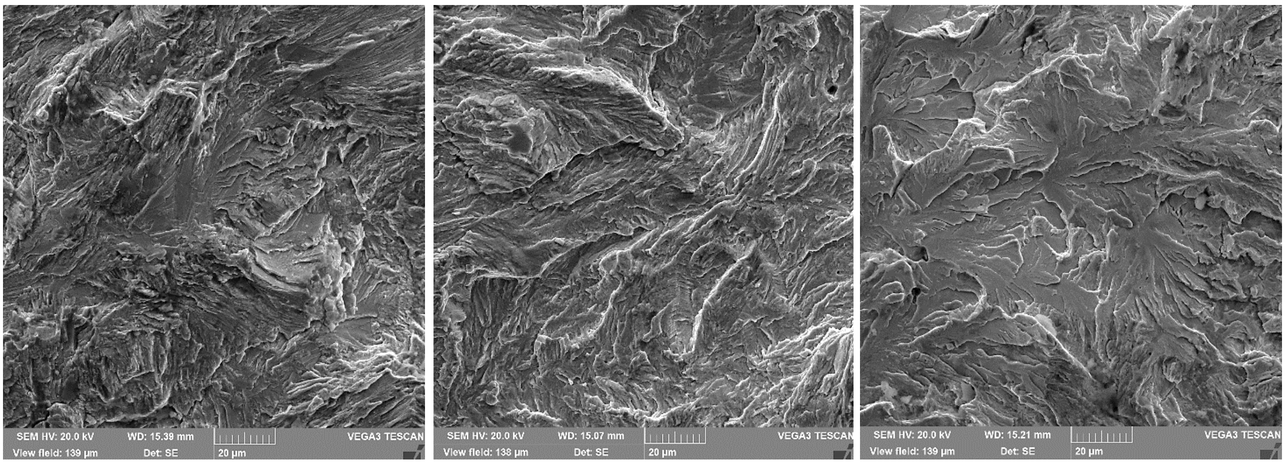
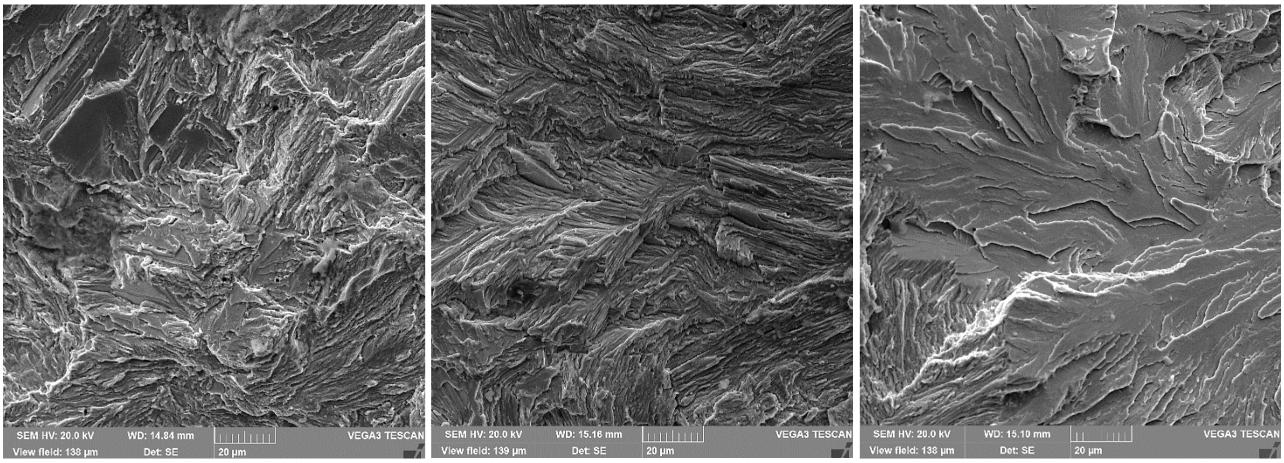


Figure 11. *da/dN x ΔK* plot for the two steels.



(a) da/dN ≈ 10^{-7} mm/cycle. (b) da/dN ≈ 10^{-5} mm/cycle (c) da/dN ≈ 10^{-3} mm/cycle.

Figure 12. Fracture surface of a CS specimen cyclically loaded at different crack growth rates.



(a) da/dN ≈ 10^{-7}mm/cycle. (b) da/dN ≈ 10^{-5}mm/cycle (c) da/dN ≈ 10^{-3}mm/cycle.

Figure 13. Fracture surface of a MS specimen cyclically loaded at different crack growth rates.

4. CONCLUSIONS

Considering that the application of pearlitic steels on railroads will certainly involve the fatigue phenomenon, the mechanical behavior of materials subjected to this degrading process is obviously important. Thus, AREMA type standards for materials characterization need to take into account this knowledge. In the materials selection for that application, the use of microalloyed steels with Nb and V is therefore an important option to ensure the best performance in service in terms of fatigue crack initiation and growth resistance.

5. ACKNOWLEDGEMENTS

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