

COB-2021-2126

CORRELATION BETWEEN INTERLAMELLAR SPACING AND HARDNESS OF A PERLITIC RAIL

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Abstract. *The need for research to increase the efficiency of the wheel-rail system is essential for the improvement of the world's railroads. The present study seeks to characterize a hypereutectoid steel rail with pearlitic matrix as to its interlamellar spacing and hardness. The vertical pins were cut (in 5 mm increments) from the surface to a depth of 20 mm in the direction transversal to the rolling of the rail. Each position was analyzed by means of the microhardness test. The microstructural characterization of the positions was performed via a SEM. The micrographs allowed the measurements of the interlamellar spacings in order to verify which are the relationships that the microstructure has with the distance and the hardness. It was noticed that the interlamellar spacing varies along the studied direction, however in terms of variance analysis there are no significant differences between the 0 and 5mm positions and the 10 and 15mm positions. The interlamellar spacing has a linearity relationship with the distance in the transverse rolling direction, that is, the hardness and spacing followed the Hall-Petch relationship. Therefore, understanding the associated microstructural characteristics allows the development of more effective materials for the wheel-rail system.*

Keywords: Rail, Pearlitic steel, Interlamellar spacing, Hall-Petch.

1. INTRODUCTION

The need for the expansion of the Brazilian railway modal is notorious, since due to the huge national territory, the use of railroads for transportation, especially of cargo over long distances, becomes more efficient and safe, generating lower financial and energy costs, in addition to mitigating environmental problems arising from road transport, i.e., the emission of pollutant gases. Thus, encouraging the development of this modal results in the growth of investments and modernizations in various sectors of the national economy (Vendramini *et al.*, 2020; Dantas and Fraga, 2021).

The effect of the increase in axle load transported in the railway modal combined with the reduction in the amount of composition, in order to reduce the cost of transport, favors the development of severe cycles of stress applied on the rails. Therefore, there is a need for the investigation of new materials and tribological evaluations in order to favor efficiency, safety, and competitiveness in the logistics of "high freight railroads" in the country (Chaves, 2017; Masoumi, Sinatora and Goldenstein, 2019).

Railroad rails are made of steel, which has its definition mainly by the amount of carbon, in which the eutectoid, when taken by reference the Fe-Fe₃C diagram, has a carbon composition close to 0.76% by weight of carbon. In addition, there are the hypo and hypereutectoid steels, the first, it is understood as hypereutectoid steel that has carbon up to 0.76%, while the second case is understood as the ferrous material that has carbon between the range 0.77% to approximately

1.00% carbon (Callister and Rethwisch, 2020). In this sense, the selection of the type of rail is linked to the desired mechanical and tribological properties for the loading conditions, speed, humidity and several other parameters that affect the life cycle of this railway component (Viana *et al.*, 2020).

The analysis of the tribological system becomes imminent for the understanding of the wheel-rail interaction, in which the loading and rolling conditions generate effects on the wear mechanisms. In this perspective, in certain sections of railroads, especially in curves, sliding between the contact surfaces (wheel and rail) predominates, some studies point out that, for rails of pearlitic microstructure, decreasing the interlamellar perlite spacing increases the sliding wear resistance and microhardness (Masoumi, *et al.*, 2019, Mishra, Pachauri and Singh, 2018 and Nikas, 2018). The present paper aims to analyze the effect of the relationship of interlamellar spacing and microhardness along the billet depth of a new, i.e., non-slip railroad track applied to a Heavy Haul railroad.

2. METHODOLOGY

2.1 Obtaining the samples

The study was based on the analysis of a TR68 type rail applied to a heavy haul railway. The evaluations were performed on the rail head. By means of electroerosion cutting, pins with dimensions of 20X5 mm were obtained, where Figure 1 shows the sectioned region as well as the dimensions of the pins. Besides this, 2 pins were used to obtain samples, by successive cuts via cut off, following the scheme presented in Figure 2, which made it possible to measure the interlamellar spacing and the microhardness. The rail surface was always taken as a reference and samples were taken every 5 mm until a depth of 20 mm was reached.

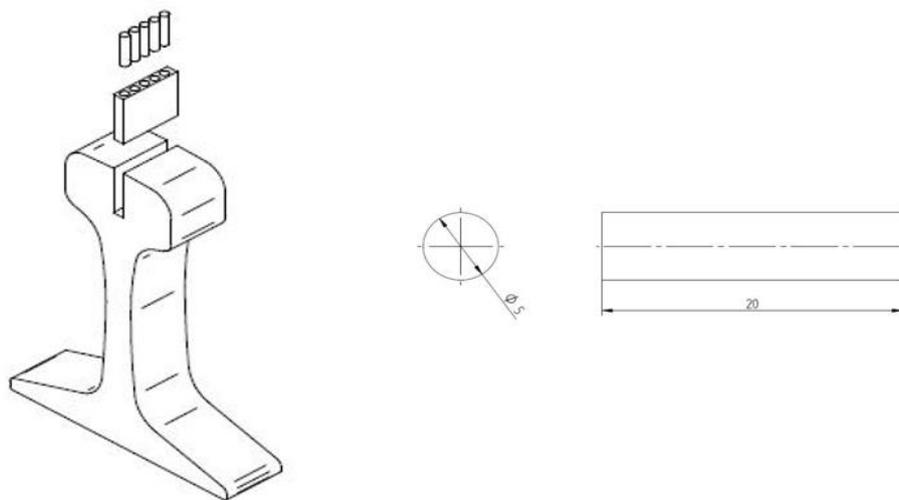


Figure 1. Pin removal arrangement along the billet and dimensions of removed pins in scale-free drawing and dimensions in mm. Source: Adapted from (Almeida *et al.*, 2019).

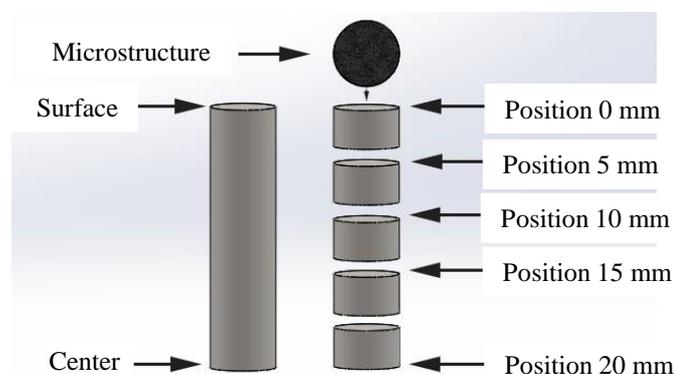


Figure 2. Schematic of the sectioning of the pins to obtain the samples on which the microhardness and lamellar spacing were determined. Source: (Authors, 2021)

2.2 Chemical analysis

Part of the billet was sectioned and evaluated by chemical analysis, via optical spectrometer with three firings for each position analyzed in the billet section. With this, it was determined that the rail is of the hypereutectoid type, from the carbon concentration. Table 1 presents the chemical composition of the analyzed pearlitic rail.

Table 1. Chemical analysis in percent by mass (% mass) of the pearlitic rail. Source: (Authors, 2021)

C	Si	Mn	P	S	Ni	Cu	Cr	Mo	V
0.880	0.280	1.200	0.010	0.002	0.020	0.004	0.190	0.010	0.020

2.3 Microstructural Analysis

The samples of the pin sectioned were embedded in Bakelite, in order to perform the metallographic procedures, that is, sanded in the following order of granulometry: 220, 320 and 600 mesh. Then, they were polished, in descending order, using diamond paste with particle sizes of 6, 3, 1 μ m. The chemical attack was performed using 2% Nital. Finally, for the analyses via Scanning Electron Microscope (SEM) the samples were placed in a beaker, with ethyl alcohol, and placed in an ultrasound, for 10 (ten) minutes, to ensure that they were clean, before being inserted in the microscope. The im

The interlamellar spacing was determined by 20 measurements of lamellae in images obtained, via SEM, in 20 different fields, in each of the 0, 5, 10, 15, 20 mm positions. Figure 3 shows the procedures performed in one field using ImageJ software. Lines parallel to the pearlite lamellae were drawn and the number of cementite lamellae intercepted per unit length was determined to obtain the average spacing (Porcaro *et al.*, 2019).

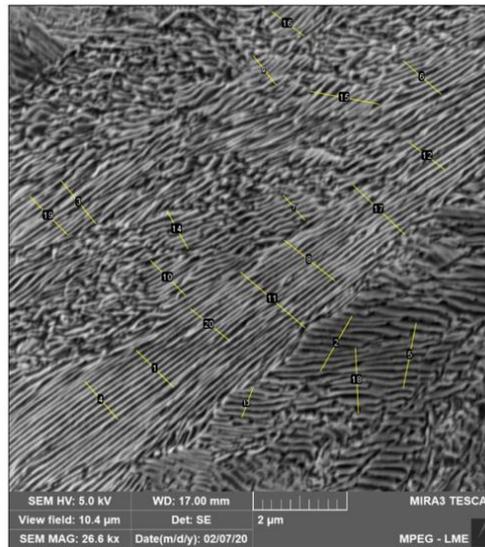


Figure 3. Exemplification of measuring a pearlitic structure with the aid of ImageJ software. (Authors, 2020)

Equation 1 determines how to obtain the interlamellar spacing (Chaves, 2017).

$$S_0 = \frac{L_t}{I}, \quad (1)$$

Where S_0 , L_t and I are interlamellar spacing, total length of intersecting line, and number of line intersections with cementite lamellae, respectively.

2.4 Microhardness analysis

Microhardness evaluation was performed using a microdurometer, in which 120 indentations were made, 30 indentations in each quadrant, of the evaluated pin sections, by means of a 50g load for a period of 30s, according to ASTM (2005) and Masoumi *et al.* (2019) literature.

3. RESULTS AND DISCUSSION

3.1 Determination of interlamellar spacing

Figure 4 shows the SEM images obtained from the microstructures of the analyzed rail. It is notable the presence of homogeneity and totally pearlitic microstructure. Considering the chemical analysis, it is noted that the mass percentage of manganese is 1.20wt.%, i.e., it has a considerable content, a fact that according to Porcaro *et al.* (2019), Mn acts as an expander of the austenitic field, which decreases the composition and the eutectoid temperature, promoting inhibition of the formation of proeutectoid phases, for this reason, in the micrographs, only pearlite is verified, even for a steel with carbon content above 0.88wt.%.

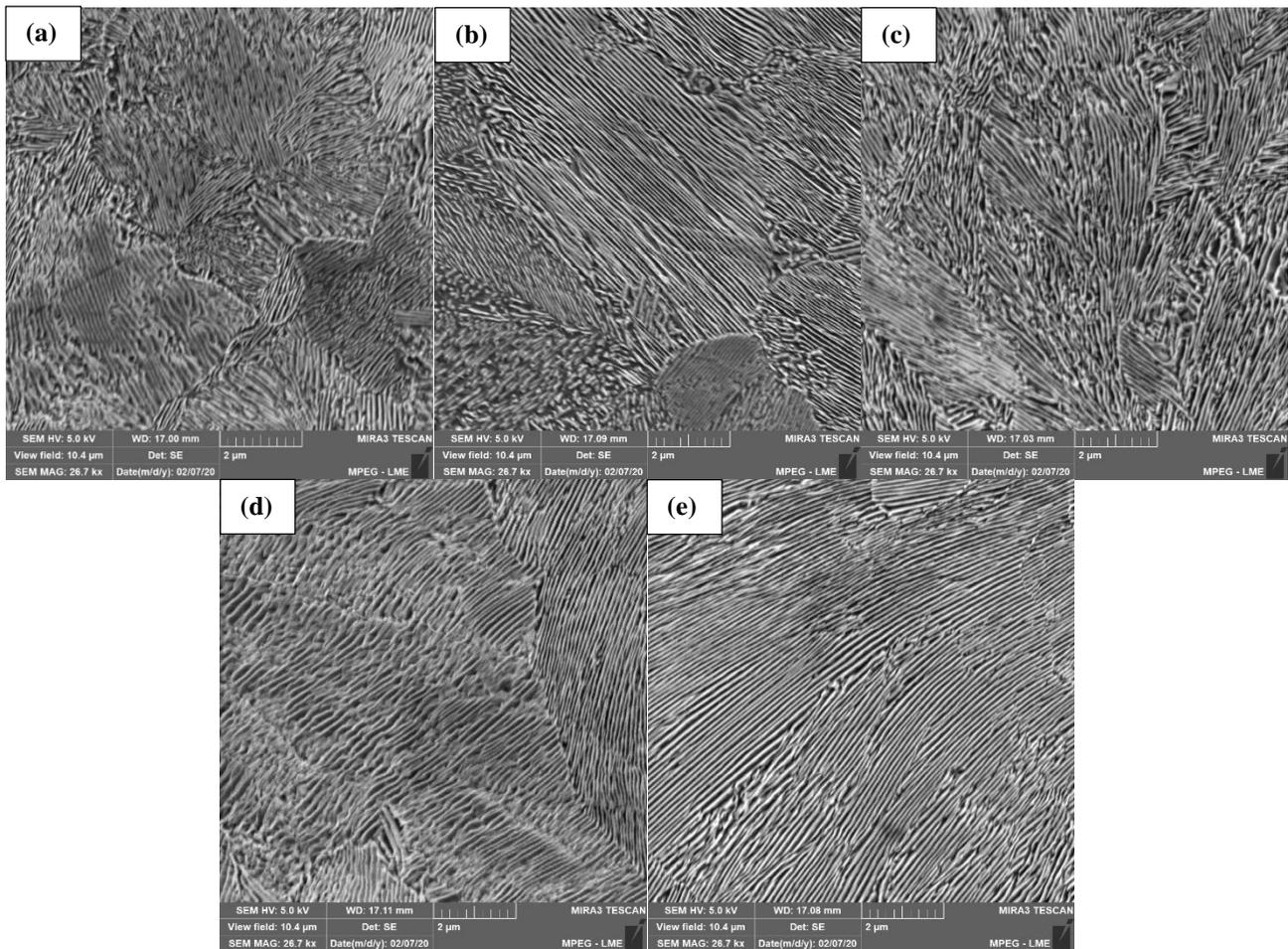


Figure 4. Electron microstructures of the 0mm (a), 5mm (b), 10mm (c), 15mm (d) and 20mm (e) positions. Source: (Authors, 2021)

From the micrographs it was possible to obtain the interlamellar spacings, which are shown in Table 2, for each position analyzed. The analysis of variance (ANOVA), considering $p < 0.05$, showed that the analyzed positions have differences among themselves. This fact indicates that, effectively, there is a significant variation for the lamellar spacing of the pearlite, consequently, different mechanical properties (hardness and tensile strength), since these properties have an inversely proportional relationship with the interlamellar spacing (Maya-Johnson *et al.*, 2015).

Table 2. Interlamellar spacing measured at different billet positions. Source: (Authors, 2021)

Position (mm)	Interlamellar spacing (nm)
0	115.93±34.16
5	119.44±34.02
10	131.66±37.53
15	130.82±40.86
20	140.42±32.64

In the evaluation in pairs, that is, by means of the t-test, it is verified that there is a difference between the various positions studied for $\rho < 0.05$, it can be seen that all positions present significant differences in their means, except for the pairs 0 and 5 mm and at 10 and 15 mm. In view of this, it can be contacted that until approximately 5 mm below the surface, the interlamellar spacing remains homogeneous, taking as reference the direction transverse to the rolling direction of the rail. Therefore, it can be stated that no significant changes occur with regard to the mechanical properties in these ranges.

3.2 Correlation between microhardness and interlamellar spacing

The results obtained for microhardness, as well as for interlamellar shielding, which are also related through the reciprocity of interlamellar spacing, are presented in Table 3.

Table 3. Measurement of microhardness, interlamellar spacing and reciprocity in relation to the sample position. Source: (Authors, 2021)

Position (mm)	Microhardness (HV)	Interlamellar spacing (nm)	Root of the reciprocal interlamellar spacing ($\text{mm}^{-1/2}$)
0	365.97±30.97	115.93±34.16	96.77
5	358.82±20.79	119.44±34.02	94.88
10	337.10±26.33	131.66±37.53	90.36
15	322.27±22.48	130.82±40.86	90.94
20	300.06±17.25	140.42±32.64	86.28

Figure 5 presents the linearized plots for the position of the samples taken from the billet in relation to microhardness and interlamellar spacing, respectively. Figure 5.a shows that microhardness (HV) is inversely proportional to position (X). However, the opposite case occurs in Figure 5.b, where interlamellar spacing (S_o) has a directly proportional relationship with position relative to surface.

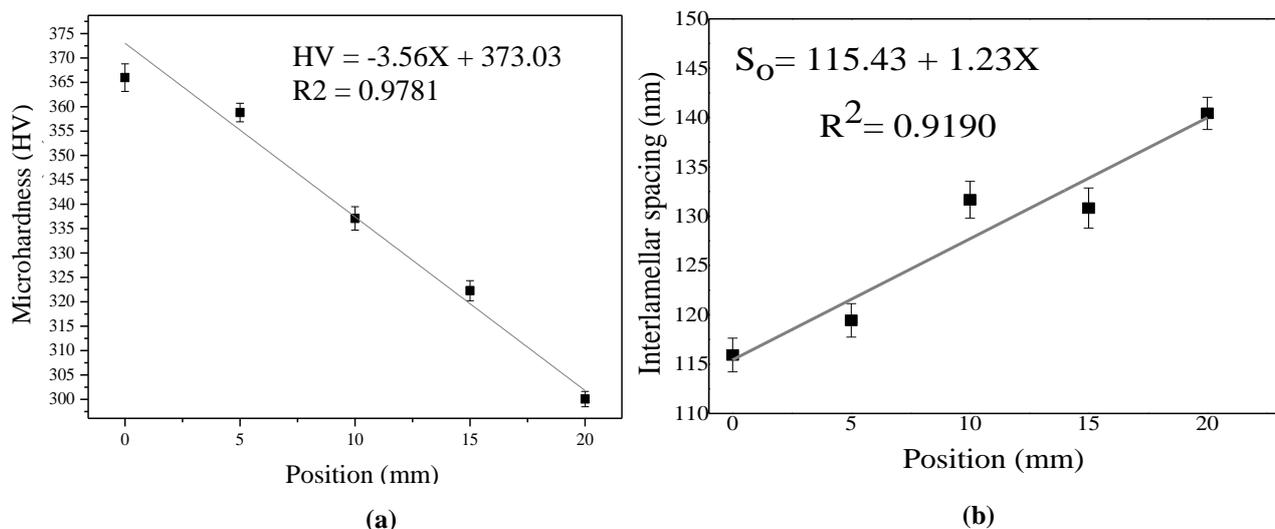


Figure 5. Relationship of microhardness (a) and interlamellar spacing (b) with the positions of 0, 5, 10, 15, 20 mm. Source: (Authors, 2021)

The relationship between microhardness and the reciprocal root of interlamellar spacing is established in an inversely proportional manner, as predicted in the literature (Krauss, 2005 and Mishra *et al.*, 2018) . Furthermore, the variation of interlamellar spacing and microhardness as a function of depth is exposed in the work of Kuziak *et al.* (2019) who, in their numerical analyses, hardness decreases while interlamellar spacing increases with billet depth.

The determination of the relationship between microhardness with reciprocity, via the Hall Petch relationship is seen in Figure 6.

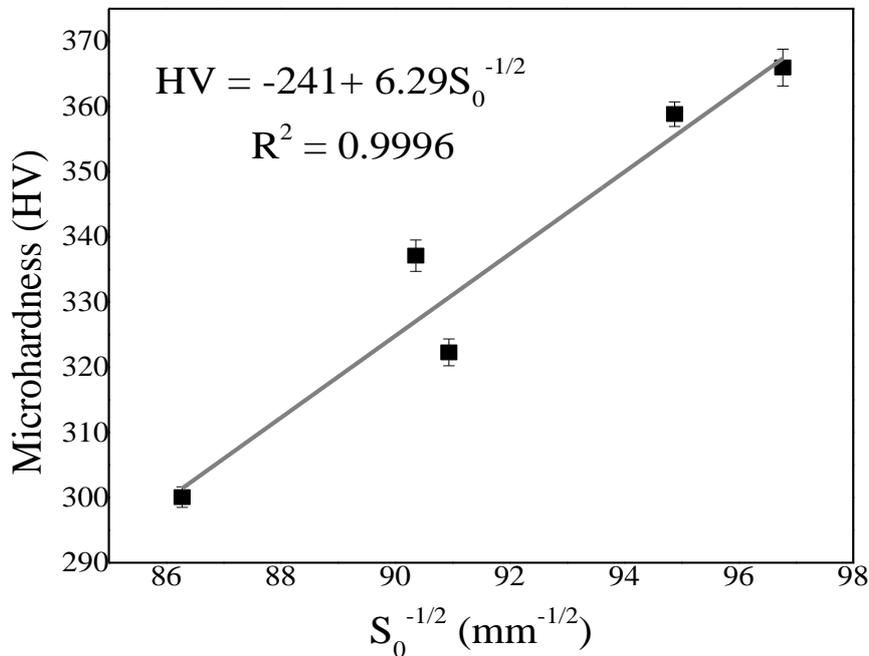


Figure 6. Comparison of microhardness and root of interlamellar spacing reciprocity. Source: (Authors, 2021)

The analysis of Figure 6 evidences that an R^2 is close to 1, that is, it presents high significance. This demonstration indicates that there is a correlation between the root of the reciprocal of interlamellar spacing and microhardness, as presented in Figure 6. The linear trend between hardness and the inverse square root of the interlamellar spacing, therefore, can be proven, that there is a Hall-Petch type relationship. Pearlitic steels have their mechanical properties related to several microstructural parameters, however, interlamellar spacing has the highest degree of effectiveness (Perez-Unzueta and Beynon, 1993; Wang, Zhang and Yang, 2017; Kuziak *et al.*, 2019). Mechanical properties, not infrequently, are dependent on the formation of the pearlitic structure, therefore, based on the analysis of Figure 6, it can be seen that for low lamellar spacings, there is an enhancement of mechanical properties, in the case of hardness and, as a consequence of this, wear resistance.

4. CONCLUSION

The analysis of the interlamellar spacing of the rails shows differences as one moves from the surface towards the central position. Therefore, it can be seen that the manufacturing process promotes changes in the microstructure, in the direction transversal to the rolling of the rail.

With regard to the analysis of interlamellar spacing, from the surface to a depth of 20 mm, it can be inferred through ANOVA that there are differences between the positions evaluated. Furthermore, in the pairwise analysis, via t-test, that there is no significant mean variation between the positions 0 and 5 mm and 10 and 15 mm, for $p < 0.05$.

Finally, it was verified that there is a correlation between microhardness and the square root of the reciprocal of the interlamellar spacing, for the positions evaluated, consequently there is a Hall Petch type relationship.

5. ACKNOWLEDGEMENTS

The authors thank the Federal University of Pará for the space to carry out the research, as well as Emílio Goeldi Paraense Museum for the SEM. In addition, thanks is given to the Project Cátedra Roda-trilho for the research materials and financial support.

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