NIOBIUM IN Si-Mn RAIL STEEL †

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Abstract

The research center of the Brazilian National Steel Co. has been conducting studies on niobium bearing Si-Mn rail steel as an alternative way to improve railway service performance. In this work, strengthening mechanisms through microalloying additions of niobium in Si-Mn rail steel are reviewed and its metallographic, mechanical and weldability characteristics are presented. The results from laboratory tests, (fracture mechanics, wear resistance and rolling contact fatigue), as well as from in-service tests carried out on two Brazilian heavy haul railways are analyzed.

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Introduction

The Brazilian National Steel Co. - CSN - a fully integrated iron and steel plant, has a special tradition in rail manufacturing in South America. Rails, essentially based on carbon and manganese, have been produced according to ASTM-A-1 specifications since 1947.

As a result of higher axle loads, longer trains, more intensive traffic and so on, the rail life of iron ore tracks has been shortened. Occurrence of contact fatigue defects and frictional wear are observed in standard carbon rails. Thus, to increase rail life for heavy duty tracks it is essential to improve the steel properties.

There are two alternative methods which can achieve to obtain improved rail properties; one is through alloying additions and the other through heat treatment. CSN has designed a niobium bearing silicon-manganese rail steel aiming at low cost, own technology and domestic raw materials.

Theoretical Aspects

In order to withstand the increasing loading conditions on railways due to heavier traffic and higher speeds, the rails must have some important characteristics such as:

- higher yield and ultimate tensile strength
- higher hardness
- high wear resistance
- high fatigue resistance
- high resistance to crack initiation and propagation
- low susceptibility to hydrogen cracking
- good weldability

Since many of these properties are mutually exclusive, and therefore, the metallurgical mechanism to achieve them must be well analyzed and balanced before being put into practice.

One of the methods by which higher strength rail steel is produced is through heat treatment. This route for CSN would require high investment on heat treatment installations and additional space in its plant.

Under such circumstances the development of a high alloyed steel was envisioned as a natural solution to the production of high strength rails.

The major concern, besides achieving the required properties, was to minimize cost. Therefore, the selection of the alloying elements was made in such a way as to use cheaper raw materials. Imported raw materials were eliminated from the development specifications.

Chemical Composition

The basic elements chosen to develop the steel were manganese, silicon and niobium. The carbon content was kept to the usual level (0,75%) giving a fully pearlitic microstructure.

Manganese has several effects on the properties of high carbon steel, but its addition to Niobras 200 steel was made to reduce the size of pearlite colony and at the same time to diminish the interlamellar spacing by lowering the transformation temperature. The manganese content (1.25%) was balanced to obtain a compromise between toughness and high strength, which are two conflicting requirements. Silicon (0.80%) was chosen as an alloying element due to its significant effect on wear resistance.

Niobium (0.03%) was added to refine the austenite grain size and, therefore, to refine pearlite colonies. This is caused by action of niobium carbonitrides which retard austenite grain growth and recrystallization by means of an interface pinning mechanism.

Microstructure Features

The microstructure plays a very important role in achieving the required mechanical properties for a steel. The two interacting processing parameters to control the steel microstructure are the chemical composition and the thermo-mechanical treatment.

The Niobras 200 steel development was aimed at achieving a fine grained pearlite colony having a very small interlamellar spacing and, consequently, producing a higher strength steel. The interlamellar spacing in a pearlite steel is a result of lowering the transformation temperature as shown in Figure 1. Manganese is an important element in obtaining such results since it depresses the transformation temperature.

The pearlite colony size which affects toughness can be reduced by controlling the austenite grain size. One way of achieving this is by adding niobium to steel.

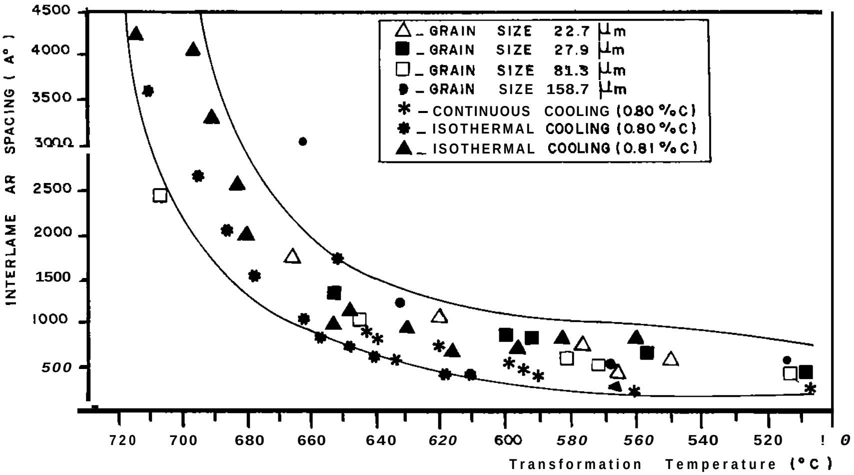


Figure 1. Transformation temperature effects on interlamellar spacing.

At normal reheating temperature, and for the chemical composition of Niobras 200 steel, one part of the niobium addition goes into solution and the other remains as carbonitride precipitates. During rolling, the soluble fraction of niobium promotes additional carbonitride precipitate formation, but of a smaller size and, therefore, more effective for austenite conditioning. The pinning of grain boundary by the precipitates and the delay in austenite recrystallization promoted by niobium would contribute to a fine grained austenite.

The microstructure obtained by the designed chemical composition for Niobras 200 is pearlitic with both fine interlamellar spacing and colony size.

Rail Steel Production and Quality Control

At CSN, the crude steel is made in LD converters and poured into hot topped ingot moulds. The ingots are soaked in pit furnaces to rolling temperature, rolled into blooms and then air cooled. After being reheated, the blooms are rolled on a break down mill and thereafter on a 3 stand structural mill for the finished shape. The rail cooling is controlled to reduce hydrogen content aimed at avoiding "shatter cracks" occurrence. Following finishing operations the rails are submitted to surface inspection and dimensional checks. When required, non-destructive testing is also applied. Except for a few modifications, the production of Niobras 200 rails follows the manufacturing and processing schedules for ASTM-A-1 carbon rails.

More than 100,000 tons of Niobras 200 rails have been produced in sections comprising 45, 52, 57 and mainly 68 kg/m. They have been submitted to the routine quality control tests, and so far the results obtained have been within the anticipated limits. The hardness and tensile properties covering the production of Niobras 200 are presented in Table I.

In addition, another program of tests has been set up for an effective assessment of Niobras 200 rail steel. The results presented previously (1) are summarized as follows:

Chemical Analysis: The homogeneity and reproducibility of chemical composition were satisfactory. The hydropen ranged from 2.5 to 4.5 ppm in LD melted steel. These values were reduced to less than 2.5 ppm in the finished product.

Internal Quality and Microstructure: Niobras 200 steel presented low concentration of inclusions, normal sulfur segregation pattern and homogeneous sound internal quality. It also exhibited fully pearlite structure.

Hardness and Tensile Properties: All the tensile and hardness testing results were within the specified values for extra hard rail steels. The homogeneity and reproducibility of the mechanical properties were also pood.

Fatigue Resistance: The endurance fatigue resistance of Niobras 200 steel under uniaxial loading tension, torsion and bending was higher relative to similar strength rail steel and could cope with the expected in-service complex system of dynamic stresses.

Impact Properties: Despite its higher strength, the V notched Charpy and notchless Charpy impact values for Niobras 200 steel were comparable to those for ASTM-A-1 carbon steel and even better than those for similar strength rail steel.

Table I. Mechanical properties of Niobras 200 rail steel.

RAIL SECTION	Yield Strength (MPa)		Ultimate Tensile Strength (MPa)		Elongotion (%)		Reduction of Area (%)		Brinell Hardness 3000 kgf	
	$\bar{X}$	6	$\bar{X}$	6	$\bar{X}$	6	$\bar{X}$	δ	$\bar{X}$	δ
45 Kg/m n. of heats : 72	615	3,5	1080	3,5	12,0	1,5	23,5	3,5	294	10
52 Kg/m n. of heats : 12	609	1,6	1085	2,0	12,0	1,6	23,5	2,0	298	5
57 Kg/m n. of heats : 85	616	2,5	1090	3.0	11,6	1,8	25,5	4,0	302	10
68 Kg/m n. of heats : 171	625	3.0	1091	3.7	11,0	1.5	21,0	4,3	307	13

Wear Resistance: Abrasive wear weight loss of Niobras 200 steel was reduced by a factor of two as compared to ASTM-A-1 carbon steel.

Laboratory Investigations

After HHRC (1), efforts have been made to better analyze the niobium effects on high carbon steels and also to determine the wear and fracture behavior of Niobras *200* steel. This research program has been carried with the cooperation of some Brazilian Universities *(2-4)* and although it is still under way, some important facts have been observed.

Niobium Effects on Microstructure

Niobras 200 steel exhibits fully pearlite structure with average inter-lamellar spacing of approximately 0,19 μm. The pearlite colony size is small when compared to a Cr-Mn-Si steel for extra hard rail, previously produced at CSN, as shown in Figures 2 and 3. These results tend to show that the microstructure of high carbon steel, is influenced by niobium additions. Kestenbach *(4)* investigated the effects of different amounts of niobium in high carbon (0.75%) steel. His work concentrates on the formation of eutectic carbides but it also demonstrates the effect of niobium on restraining austenite grain growth, Figure *4.* This effect is probably due to NbCN pinning action on interfaces (5).

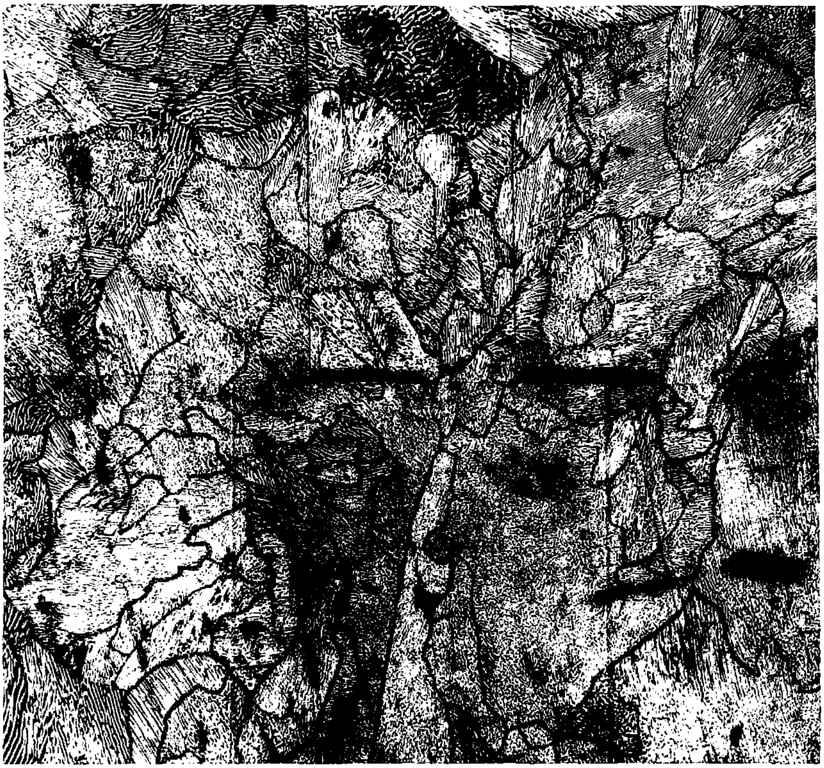


Figure *2.* Microstructure of Niobras 250 rail steel - SEM.

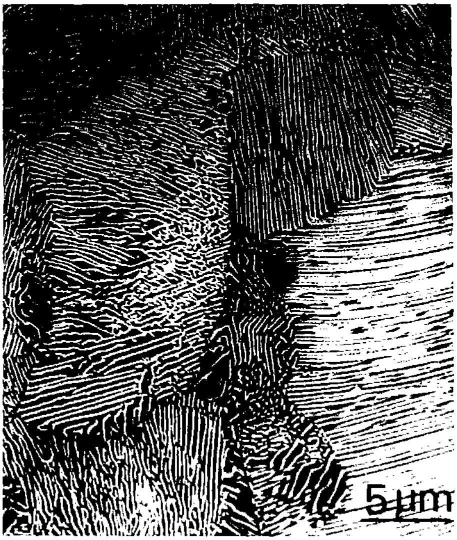


Figure 3(a). Niobras 200 steel.

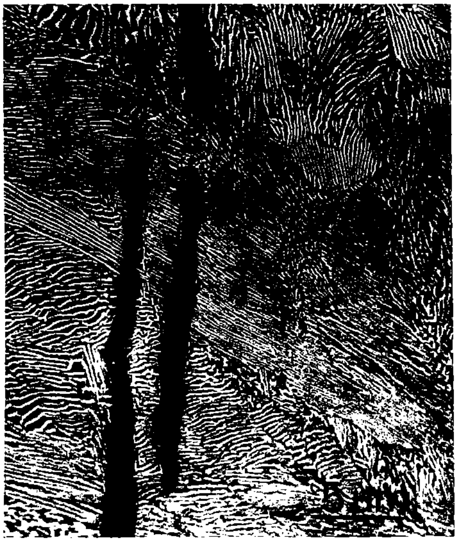


Figure 3(b). Cr–Mn–Si steel.

Figure 3. Pearlite morphology of Niobras 200 and Cr–Mn–Si steel.

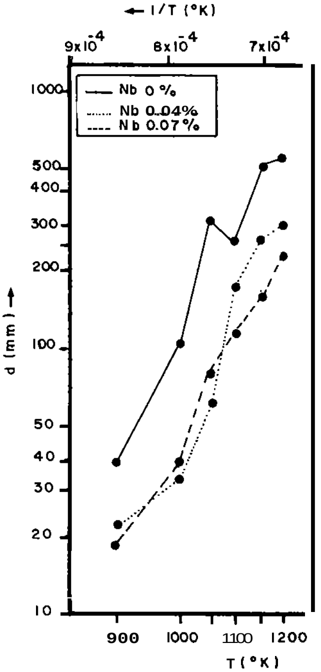


Figure 4. Austenite grain growth in niobium bearing high carbon steel.

Wear and Contact Fatigue Characteristics

The best way to evaluate wear and contact fatigue characteristics of any product is to test it under real service conditions. However, in such cases, the results would be very much influenced by track or train parameter variations and furthermore, trial test would take longer time. For these reasons, laboratory tests have been carried out in Niobras 200 rail to predict wear and contact fatigue behavior of this rail when in service. Three different types of rails, ASTM-A-1 carbon steel, Cr-Mn-Si steel and a heat treated rail steel, have also been tested for comparative purposes as shown in Table II.

Wear Resistance. This test was conducted on an Amsler Machine under the conditions presented in Figure 5a. The specimen weight loss from the wear test is plotted against rail life expressed by the number of revolutions as shown in Figure 5b. Each point in the graph is an average of the results obtained from three specimens tested.

It can be noticed that the rail weight loss is influenced by both its hardness and its microstructure. The fully pearlite rail steels exhibit high wear resistance which increases as the interlamellar spacing and pearlite colony size decrease. The good behavior of Niobras 200 steel is due to its pearlite morphological characteristics.

Figure 5c shows the hardness variation across a transverse section of the specimens after wear test. Plastic flow in similar amounts was found for the Niobras 200 steel compared to the Cr-Mn-Si steel and heat treated rail steel.

Table 11. Chemical composition, mechanical properties and microstructure of laboratory test rails.

RAIL TYPE	Chemical Composition (%)							Mechanical Properties			Microstructurel Characteristics
	C	Mn	Si	P	S	Cr	Nb	Tensile Strength Mia	Elong. (%)	Brinell Hardness	
ASTM-A-I	0,78	0,90	0,14	0,026	0,026	—	—	960	8.5	269	fully medium pearlite
Cr-Mn-Si	0,69	0,98	0,54	0,020	0,026	1,10	—	1076	8,6	314	fully fine pearlite
NIOBRAS 200	0,73	1,38	0,76	0,019	0,022	—	0,028	1089	10.2	314	fully fine pearlite
HEAT TREATED	0,64	1,10	0,22	0,015	0,013	—	—	1137	12	327	tempered rnartensite

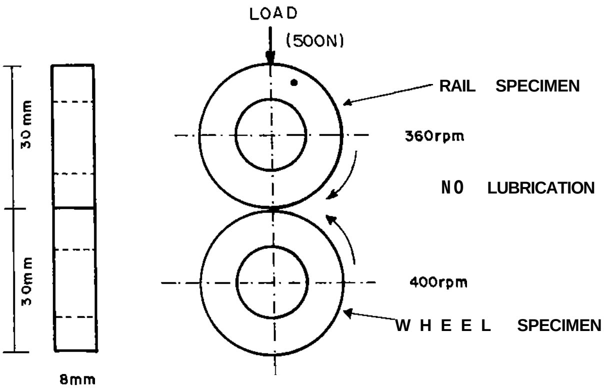


Figure 5(a). Test method.

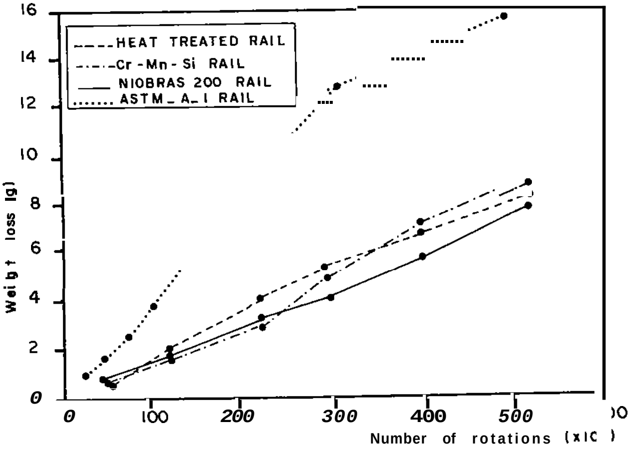


Figure 5(b). Wear loss curves.

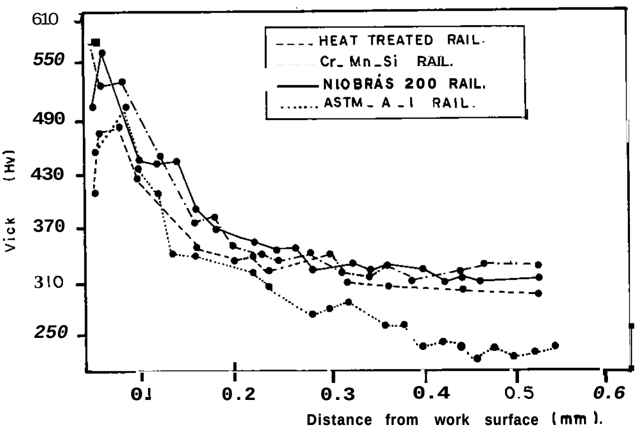


Figure 5(c). Hardness variation.

Figure 5. Wear test

Contact Fatigue Resistance. As previously mentioned, rails under high axle load do not achieve their expected wear life, requiring replacement due to contact fatigue defects such as heat checks, flaking and shelling.

In order to assess the resistance of Niobras 200 steel against the initiation and propagation of contact fatigue cracks, a simulation test was performed at CSN. The test method differs from the wear resistance test in the shape of the specimens and in the use of lubricant between the test discs, as shown in Figure 6a.

The resistance to the initiation of contact fatigue cracks, for the different rail types tested is shown in Figure 6b. As can be observed, Niobras 200 steel shows higher crack initiation resistance than those determined for the reference test rails. In addition, the crack propagation results, as Figures 6c and 6d show, indicate that Niobras 200 exhibits good resistance to fatigue crack growth. The encouraging results from Niobras 200 steel in these tests are probably related to its microstructure characteristics.

It can be stated that both wear resistance test and contact fatigue simulation test can be used to make qualitative predictions as similar performance was found in actual rails tested under real service conditions. The Niobras 200 rails performance on these tests indicate that they are an economical alternative to be used in the Brazilian heavy haul railways.

Fracture Crack Growth

The Niobras 200 steel crack growth behavior was analyzed by Chawla (3) in comparison to ASTM-A-1 and Cr-Mn-Si steels. The crack growth rate obtained

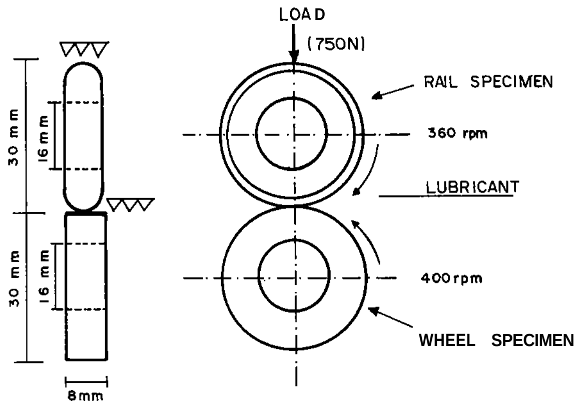


Figure 6(a). Test method.

Figure 6. Contact fatigue test.

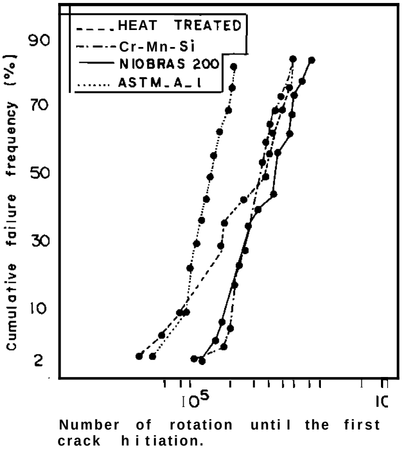


Figure 6(b). Contact fatigue crack initiation curves.

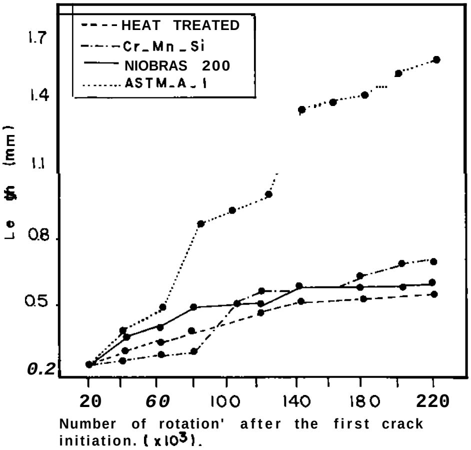
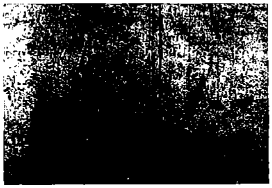


Figure 6(c). Contact fatigue crack evolution curves.



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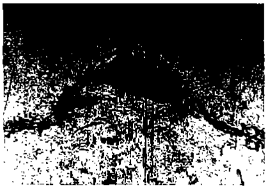

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Figure 6(d). Observation of crack propagation in Niobras 200 rail steel.

Figure 6. Contact fatigue test.

for the ailoyed rails is presented in Figure 7, as crack growth rate V relative to stress intensity factor. Table III shows the calculated values of the materials constant m and c according to the Paris Equation:

$$da/dn = c\ (k)^m \tag{1}$$

When comparing Niobras 200 steel m and c values to those of Cr-Mn-Si steel as well as those of various types of high strength steels, as analyzed by Marich, one can observe that the fatigue behavior of Niobras 200 steel is good. This is because its m and c values are relatively low. The above is also illustrated in Figure 8 where the stress intensity factor ranges from 20 to 50 MPa $\sqrt{m}$. 'Chis means that Niobras 200 steel fatigue crack growth rate is relatively slow, showing that it will have adequate in-service fatigue behavior.

Weldability Analysis

The two welding processes commonly used for joining rails are flash butt welding and thermit welding.

Both cause great changes in the steel microstructure, which in turn affects the mechanical properties and, therefore, the service performance.

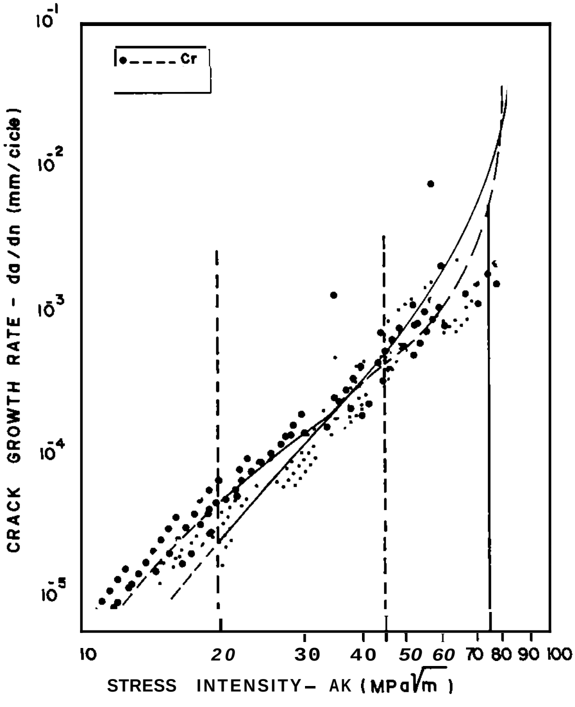

Figure 7. Crack growth curves.

Table III. m and c parameter values of different rail steels.

Steel / Parameters	NIOBRAS 200	Cr-Mn-Si	Standard Carbon	Heat Treated	Rails Tested By Marich
m	3.80	3.02	4.23	3.43	4.83 - 8.42
C	3.5×10^{-10}	6.8×10^{-9}	2.62×10^{-10}	6.16×10^{-10}	5.51×10^{-16} 2.3×10^{-11}

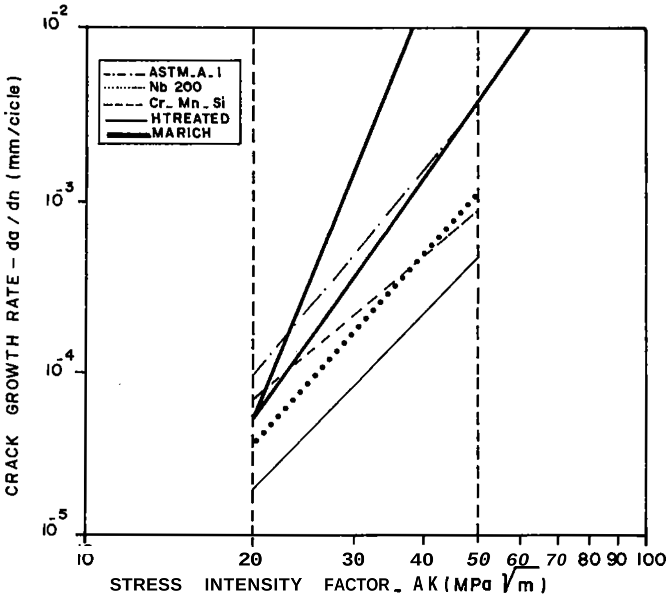

Figure 8. Crack growth curves.

In any welding operation it is important to analyze the influence of the thermal cycle on steel properties. If the cooling rate reaches its critical value, martensite is formed and this can be very detrimental to the mechanical behavior of the rails.

In order to analyze the weldability characteristics of Niobras 200 steel, CSN conducted studies on its welding behavior when subjected to welding operations by the two processes mentioned above.

The main emphasis was, however, concentrated on the flash butt welding process because it is more widely used than thermit welding. In addition, the cooling rates of welded joints made by the flash butt welding process are greater than those of thermit welding, and therefore, much more critical in terms of martensitic transformation.

With this in mind, a series of experiments was carried out using 15 different welding conditions. The purpose was to identify welding procedures which could minimize both the amount of brittle constituents and the welding time.

The main welding procedure variables were chosen according to Table IV. It can be seen from this the experiments were established in such a way that, €or each set of welding variables, a post heating treatment of 50 and 75 seconds was applied. This was aimed at verifying the influence of that treatment on cooling rates and consequently on martensite formation.

The rail samples were welded using attached Pt/Pt-Rh termocouples to record the thermal cycles. The samples were then subjected to a set of tests which comprised the determination of the following characteristics:

- Chemical analyses
- Hardness
- Macro and microstructure
- Microhardness
- Central line microstructure
- Tensile properties
- Fatigue properties

Table V shows the volumetric fraction of martensite plus bainite in the microstructure as measured in the central line of the welded joints. It can be seen that all values, but one, are below 10 percent martensite. Heller *(6)* has shown that martensite plus bainite levels up to the above value are not detrimental to service performance.

After checking all the results of this study it was concluded that Niobras 200 steel is a good weldable steel. Welding with flash butt machines can be performed by utilizing several welding procedures even without post-heating. This can be considered as an advantage since post-heating treatment lowers productivity. It should be pointed out that the good weldability of Niobras 200 steel might arise mainly from its reduced hardenability when compared to alloyed rails of similar strength.

The results and details from Niobras 200 steel welding studies have been reported by Fernandes (7), and will not be further discussed here.

Niobras 200 welded joints performance, evaluated under real service conditions, confirmed the laboratories results by showing no occurrence of defects.

Welding Condition	Welding Procedure	Contact Time (sec)	Pressure Time (sec)	Pos - Heating Time (sec x 10^3)
0	0A	2.0	0.6	—
0	0B1	2.0	0.6	50
0	0B2	2.0	0.6	75
1	1A	0.6	0.2	—
1	1B1	0.6	0.2	50
1	1B2	0.6	0.2	75
3	3A	3.0	1.0	—
3	3B1	3.0	1.0	50
3	3B2	3.0	1.0	75
4	4A	3.0	0.2	—
4	481	3.0	0.2	50
4	482	3.0	0.2	75
5	5A	0.6	0.6	—
5	581	0.6	0.6	50
5	582	0.6	0.6	75

Figure 4. Welding parameters.

In Service Performance

The first in service performance evaluation of Niobras 200 rails (57 kg/m in section), in both curved and straight RFFSA* track, as compared to ASTM-A-1 and Cr–Mn–Si rails, produced at CSN, was presented in HHRC (1) and in IENTTFA** (8). The above work showed that Niobras 200 steel and Cr–Mn–Si steel were similar in wear resistance and both exhibited by far, a superior performance when compared to ASTM-A-1 carbon steel.

Concerning contact fatigue, Niobras 200 steel exhibited much better performance than the Cr–Mn–Si steel.

Another in service performance evaluation at RFFSA (9) was conducted at Curitiba–Paranagua railway track. This railroad operates track (45 kg/m rail section) through mountains carrying approximately 6,5 MGT***/year of soy beans. The maximum axle load is 20 tons and the 36 km track extension is composed of tight curves as follows:

Curve radius (m)	<90	<100	<120	<150	<200	>200	straight
%over the track extension	6	27	6	8	5	11	37

Under such conditions, the stresses applied to the rails are very high and, therefore, substantial amounts of metal flow and wear loss are found on the ASTM-A-1 carbon rail head. After only 5 months of service, approximately 3 MGT of traffic, this rail steel had to be replaced at the tighest curve due to excessive wear.

The Niobras 200 rails were placed on this track, in September, 1978, and since that time the profile measurements have been repeated after 3, 6, 12, 18, 24 and 30 months.

It was predicted that after 30 months of inspection Niobras 200 test rails would only require replacement after surpassing 20 MGT of traffic. Thus, the use of Niobras 200 rails in this railroad results in an significant cost saving despite its price being slightly higher than that of the ASTM-A-1 rails. It must also be pointed out that in this geographic region the winter temperature reaches - 10 C, which could contribute to fracture, but none was found. This demonstrates its good toughness property.

Niobras 200 rails (57 kg/m section) have also been used in CMRJ† and CMSP†† metropolitan tracks with satisfactory results. This has contributed to reducing maintenance costs.

At present, Niobras 200 rails (68 kg/m section) are being tested at the iron ore transportation main lines of Vitoria - Minas Railway (CVRD) and at Belo Horizonte - São Paulo track of RFFSA. The service conditions, in both tracks, are among the most severe in the world due to high axle loads, high traffic intensity and density associated with low curve-radius.

In CVRD track, four types of alloyed rail steels (Table VI), including Niobras 200 rails, were laid on 5 curves of different degrees of curvature.

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* RFFSA: Brazilian Railway Co.
** IENTTFA: First Brazilian Meeting on Rail Technology
*** MGT: Million Gross Tons
† CMRJ: Rio de Janeiro Metropolitan Co.
†† CMSP: São Paulo Metropolitan Co.

Samples	OA	081	082	1A	1B2	3A	381	382	4A	481	482	5A	581	582	1-0A	4-3A	1-4A	3-5A	2-082	3-082
Volumetric Fraction (%)	6.67 ± 0.962	0.49 ± 0.359	1.05 ± 0.608	21.16 ± 2.003	0.0	1.01 ± 0.702	0.53 ± 0.413	0.0	2.61 ± 1.297	0.58 ± 0.365	0.77 ± 0.512	0.43 ± 0.429	0.52 ± 0.381	0.0	5.27 ± 0.731	1.21 ± 0.882	3.29 ± 1.459	0.53 ± 0.278	0.0	0.28 + 0.33

Table VI. Specified chemical composition and mechanical properties of rails on the CVRD and RFFSA test tracks.

Track	Test Rails	Chemical Composition (%)							Mechanical Properties (minimun)			
		C	Mn	Si	max.	S max.	Cr	V / Nb	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Brinell Hardness
CVRD	A	0.55 0.75	0.80 1.30	0.40 0.70	0.03	0.03	0.80 1.30	V 0.03 max.	590	1080	9	310
	B	0.65 0.80	1.10 1.50	0.50 0.80	0.03	0.03	—	—	—	980	10	290
	C	0.65 0.80	1.10 1.50	0.70 1.10	0.03	0.03	—	—				
aFFSA	NIOBRAS 200	0.70 0.80	0.90 1.10	0.70 0.90	0.03	0.03	—	Nb 0.02	580	1000	8	290
	ASTM-A-1	0.67 0.80	0.10 10.25	0.70 1.00	0.04	0.05	—	—				
	E*	0.60 0.75	0.70 1.10	0.10 0.30	0.035	0.04	—	—	800	1100	14	325 375
	F*	0.69 0.82	0.50 0.80	0.15 0.35	0.035	0.04	—	—	800	1100	14	321 388

* HEAT TREATED RAILS

The test rails were installed on the inner and outer positions of the curves under identical test conditions.

The objective of the test is to study at each of the curves, rail wear, plastic flow, end downsweep and surface defects, but at individual curves, emphasis was placed on certain parameters as follows: the determination of the rail service life on the 150 m - 260 and 382 m - radius curves in relation to wear and surface defects; on a 229 m radius curve, the useful life of the rail in relation to the cross transportation. As for the curve of 343 m radius, the plastic flow is to be studied through the measurement of the deformation of 19 mm diameter and 2.4 mm diameter test pins previously inserted into the rail head at predetermined angles and locations. These test rails with pins will be taken out when the rail reaches 7 mm wear in the gauge corner so that, through X-ray, the longitudinal and transverse deformations can be detected as a measure of the plastic flow.

After 2 years of operational tests, during which period 180 MGT have passed over the rails being tested, the Niobras 200 rail steel shows satisfactory behavior in terms of wear, plastic flow, surface and weld defects.

In RFFSA, the Niobras 200 rails in service performance have been compared to ASTM-A-1 rails as well as with 2 types of heat treated rails. The rail characteristics are presented in Table VI. After 90 MGT of traffic on the test curves, considering wear progresses at the same rate, it can be expected that Niobras 200 rails will have a much greater life than ASTM-A-1 carbon rails. It will also present, when compared to the heat treated rails, a similar performance at a 345 m radius curve but slightly lower life at a 260 m radius curve so far. No contact fatigue surface defects were detected on Niobras 200 test rails.

The CVRD and RFFSA track test programs have not been finished yet. Therefore, the results herein presented can not be considered as final.

Conclusions

The extra hard niobium bearing Si-Mn rail steel "Niobras 200" is a result of Brazilian technology. Its development was based on home raw materials resources eliminating the need for imports.

The production of this rail is technical feasible at CSN. The plant productivity and operational efficiency had been kept unchanged as compared to ASTM-A-1 carbon rail steel production;

The new product is characterized by high ultimate tensile strength and fatigue resistance associated with a relative good toughness, being superior to other similar strength level rail steels in abrasive wear and in surface crack initiation and propagation.

The Niobras 200 rail is a good weldable steel by thermit and flash butt welding processes. In addition, excellent in-service results have been obtained under heavy loads and intensive traffic in iron ore railways.

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