New rail steels for the 21st century

Raymundo Ordonez
Ellwood Materials Technologies, US

C. I. Garcia
University of Pittsburgh

Anthony Deardo
University of Pittsburgh

New Rail Steels for the 21st Century

R. Ordonez[1], C. Isaac Garcia[1], Semih Kalay[2] and Anthony J. DeArdo[1,3]
1. The Basic Metals Processing Research Institute (BAMPRI), Department of Mechanical Engineering and Materials Science, University of Pittsburgh, Pittsburgh, PA 15261, USA

2. Transportation Technology Corporation, Inc, Pueblo, CO 81001, USA

3. Finland Distinguished Professor, Department of Mechanical Engineering, University of Oulu, P.O. Box 4200 (Linnanmaa), FIN-90014, Finland

KEY WORDS: Rail steels, interlamellar spacing, pearlite colony, pro-eutectoid cementite.

Abstract

As the axle loads have been continuously increasing with time, so has the desire for premium rail steels with better wear, rolling contact fatigue and fracture. A research program has been initiated to study the microstructural aspects of near-eutectoid steels that would improve these properties. The first phase of the work was to carefully characterize the existing rail steels in terms of interlamellar spacing, cleanliness and pro-eutectoid cementite. These parameters were then correlated with both mechanical properties and overall rail performance. The second phase of the program was to develop a better microstructure through control of composition, thermomechanical processing and cooling path. The mechanical properties of these new steels have been determined and the rail performance tests are being conducted. This paper will report on both phases of this research program. Guidelines for future rail compositions and processing to obtain improved properties and performance will be presented.

1. Introduction

For more than 150 years, the steel rails have been the core of the world rail systems. Its main functions are to transmit the wheel forces to the track bed and guide the vehicle throughout the route.[1] In North America, rail road system plays a very important role in freight transportation of minerals, crops and goods. In later years, the demand for increased efficiency in this system has caused an increase in both the axle loads and speed of the trains. However these demands have not come without a price, for example the increase of in-axle load induces a decline in the rail life. The average life of the rails depends on many factors including but not limited to rail quality, wheel-rails interaction and maintenance policies are among many of these factors. The average life of the rail is measured in terms of the amount of freight carry on the rail.[1] At the present time, the most common type of steels used to fabricate rails is based on a fully- pearlitic microstructure approach. These steels are typically characterized by high strength, fatigue resistance and adequate fracture toughness. Despite the large amount of research and development on rail steels,[1-5] there are several issues that remain of technological interest, for example wear resistance of a rail steel is believed to be directly related to both hardness and interlamellar spacing.[5-7] Pearlitic interlamellar spacing which is a function solely of transformation temperature for a given composition, seems to be according with current understanding the most important microstructural parameter to control hardness and wear resistance. There is no question that while interlamellar spacing is one of the most important structural factors in controlling the strength of rail steels, several other factors such as the grain boundary coverage of pro-eutectoid cementite, the cleanliness and the stereological characteristics of the non-metallic inclusions of the steel are perhaps equally important in affecting the wear and rolling contact fatigue of the rails. In the traditional design and thermomechanical processing of rail steels there appears to be a lack of understanding regarding the effect of austenite composition and grain size prior to transformation and the cooling rate on the transformation temperature, the formation of pro-eutectoid cementite and the resulting interlamellar spacing.

The first phase of this work was directed to conduct systematic microstructural analysis of the current premium rail steels in terms of interlamellar spacing, pearlite colony as well as prior austenite grain boundaries, determination of pro-eutectoid cementite and the assessment of the non-metallic inclusions. The main objective of this phase was to gain a better understanding of the effect of the microstructural features on the mechanical properties and overall rail performance.

The second phase of this work involves the alloy design and thermomechanical processing and transformation behavior of a series of new experimental steels. The major thrust of this second phase was the microstructural refinement of the austenite prior to transformation, the elimination of grain boundary pro-eutectoid cementite during cooling and the formation of fully pearlitic microstructures with fine interlamellar spacing. The results of this study will be described and presented in this paper.

2. Experimental procedure

2.1 Current understanding of premium rail steels

Samples from several commercial rail steels were cut, mounted, polished and etched for microstructural examination using standard metallographic techniques. The samples were obtained from three different locations in the rail as shown the Figure 1. Different etchants were used to reveal the microstructure of the steels. The interlamellar spacing, the pearlite colony size, the prior austenite grain size and the stereological parameters of the non-metallic inclusions were measured using different techniques. To aid in this measurement OM, SEM and an automated BioQuant NOVA image analysis system were employed. The inclusion analysis was performed in samples only from location 1.

2.2 Experimental new rail steels

Four laboratory heats were melted under vacuum condition and poured into 300# ingots. The approximated chemical composition of these steels is illustrated in Table 1. From each heat, one half of the ingot was used to develop the proper thermomechanical processing using a computer controlled high temperature MTS deformation system. The other half of the ingot was used for the hot rolling experiments.

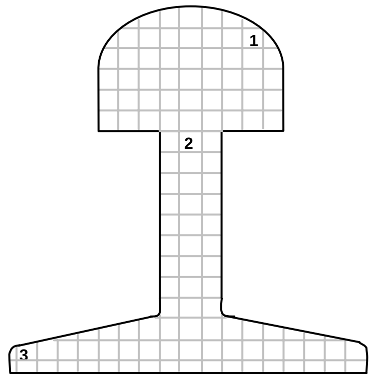

Figure 1 Rail profile, sample obtained locations.

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

	C	Mn	P	S	Si+Cr+Mo+V	Cu	Ni	Al	Nb
Rsteel1	0.8	1.0	.0026	.0021	1.47	.094	.088	.0452	.033
Rsteel2	0.8	1.2	.0061	.0024	1.38	.091	.091	.0324	.035
Rsteel3	0.8	1.0	.0069	.0018	1.34	.089	.089	.0352	.016
Rsteel4	0.8	1.2	.0075	.0023	0.99	.081	.081	.0425	.0254

2.3 Thermomechanical Processing (MTS)

The MTS compression system was used to develop the processing conditions to achieve the required microstructure and the AREMA requirements in terms of hardness (RC). In this context the required microstructures were fully pearlitic. The final as processed microstructure should have at least the minimum hardness as stated by the AREMA specification of 38 Rockwell C. The general TMP procedure as illustrated in Figure 2.

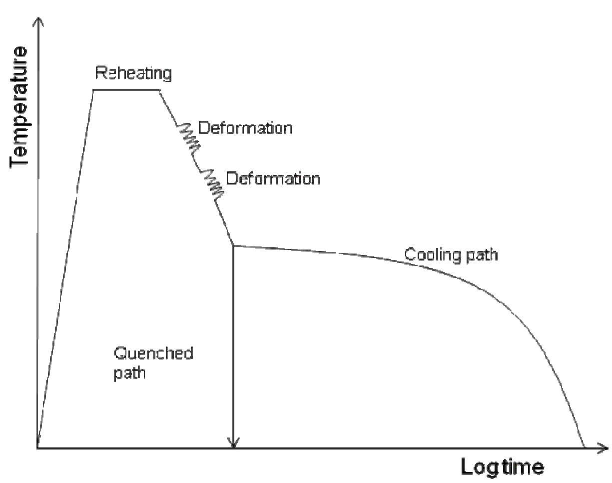

Figure 2. Schematic representation of general thermomechanical process.

Table 2 shows the best processing conditions used to produce the final required microstructure. For example, steel 1 was reheated at 1160C prior to deformation, then deformed 50% at 1100^{c}C, with the second deformation at 850^{o}C. After the deformation at 850C the sample was cooled to 550^{o}C using a cooling rate sufficiently high to avoid the formation of pro-eutectoid cementite along the prior austenite grain boundaries and then ACRT. The resulting microstructure was fully pearlitic. A similar processing procedure was done for the other steels.

Table2. TMP conditions to accomplish the AREMA requirements

	Rsteel1	**Rsteel2**	**Rsteel3**	**Rsteel4**
Reheating temperature, ^{o}C	1160	1200	1155	1200
Deformation 1 Temp., ^{o}C	1100	1150	1100	1150
Deformation 2 Temp., ^{o}C	850	880	890	850
Cooling Path	From 850 to 600 ^{o}C	From 880 to 600 ^{o}C	From 890 to 600^{o}C	From 800 to 550^{o}C

3. Results

3.1 Results from current understanding of premium rail steels

Scanning electron micrographs of pearlitic microstructures of different rail steels are shown in Figure 3. These SEM micrographs show examples of the lamellae of cementite in the typical pearlitic microstructure from the different steels investigated. The quantitative assessment of the interlamellar spacing at three positions (head, web and base) within the rail samples is illustrated in Table 3. The results from this table show that the interlamellar spacing is smaller at the head and increases at the web and base of the rail this was probably the result of the head hardening process

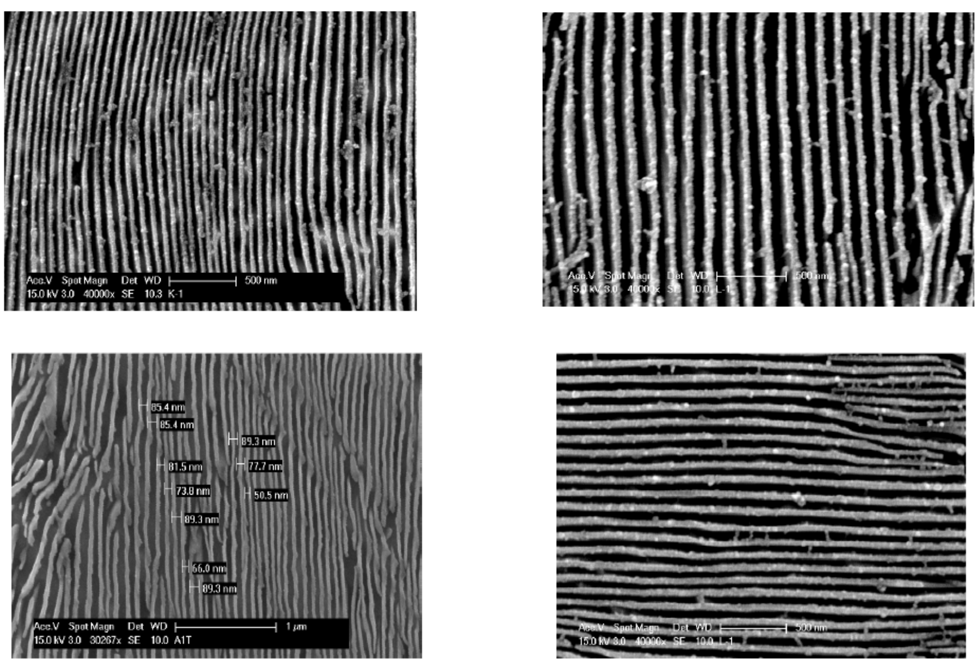

Figure 3. Typical lamellae of cementite in a pearlitic microstructure from different premium rail steels.

Table 3. Interlamellar spacing (μm) measured in commercial premium rail steels

Internal ID	Head	Web	Foot
A	0.1001	0.15	0.154
B	0.101	0.129	0.135
C	0.088	0.153	0.197
D	0.094	0.146	0.191
E	0.089	0.145	0.163
F	0.117	0.12	0.116
G	0.07	0.107	0.132
H	0.098	0.133	0.145
I	0.088	0.148	0.178
J	0.078	0.129	0.175
K	0.08	0.177	0.148
L	0.099	0.125	0.148
M	0.1001	0.13	0.152

A similar assessment was done for pearlite colony size and prior austenite grain size. Figure 4 shows some examples of typical pearlite nodules (colonies), as well as optical micrographs of prior austenite grain boundaries.

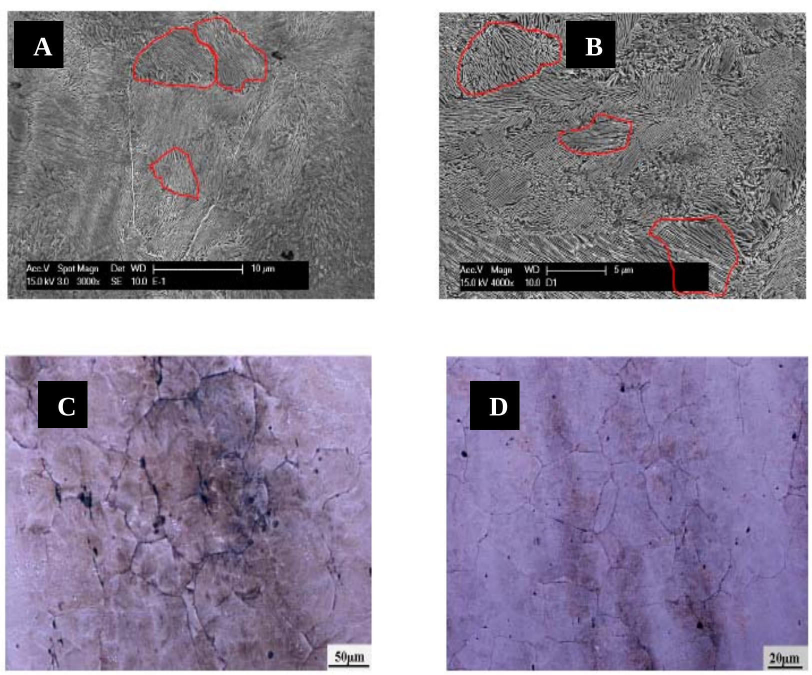

Figure 4. a) & b) Typical pearlite colonies (in red),
c) & d) Optical micrographs of prior austenite boundaries.

The results of the average prior austenite grain size and from pearlite colony size assessment from the commercial premium rail steels are shown in Table 4. These results from this table show that the pearlite colony size is slightly smaller at the head of the rail samples than at the web or base of the rail. Different behavior was observed regarding the prior austenite grain size, the smaller grains were measured at the foot location instead of at the head. The results from Table 4 also seem to support the view that the majority of the current steels used in the fabrication of rails exhibit very similar microstructural conditions of austenite prior to transformation.

Table 4. Values of pearlite colony size and prior austenite grain (μm) from different premium rail steels.

	Pearlite Colony			**Prior Austenite Grain**		
Internal ID	**Head**	**Web**	**Foot**	**Head**	**Web**	**Foot**
A	2.6	3.3	3.2	67.9	74.4	21.3
B	1.9	3.6	2.4	59.4	32.1	27.3
C	2.1	3.5	4.2	34.7	64.6	21
D	2.1	4.6	3.9	34.7	27.2	28.5
E	2.9	3.9	3.7	28.8	32.1	26.3
F	2.9	3.6	3.1	23.3	32	22.1
G	2.8	4.4	3.2	24.8	27.9	22.2
H	2.9	3.9	2.9	25.9	47.8	23.9
I	2.8	2.7	3.9	58.6	61.5	20.5
J	2.4	2.6	4.3	32.4	60.8	27.3
K	2.5	4.2	3.8	64.3	73.1	28.3
L	3.0	3.9	3.3	49.8	34.3	23.2
M	2.9	2.9	3.5	56.3	66.3	23.1

The measured values of the interlarmellar, pearlite colony size and prior austenite grain were correlated with the strength measured in these materials.. As expected, the interllamelar spacing has the major contribution to the strength. It is well-known that as the steel approaches the eutectoid composition (100% pearlite), the pearlite becomes the major contributing factor to the strength; this is controlled by the interlamellar spacing. Figure 5 summarizes the effect of the main microstructural features on the yield strength on premium rails.

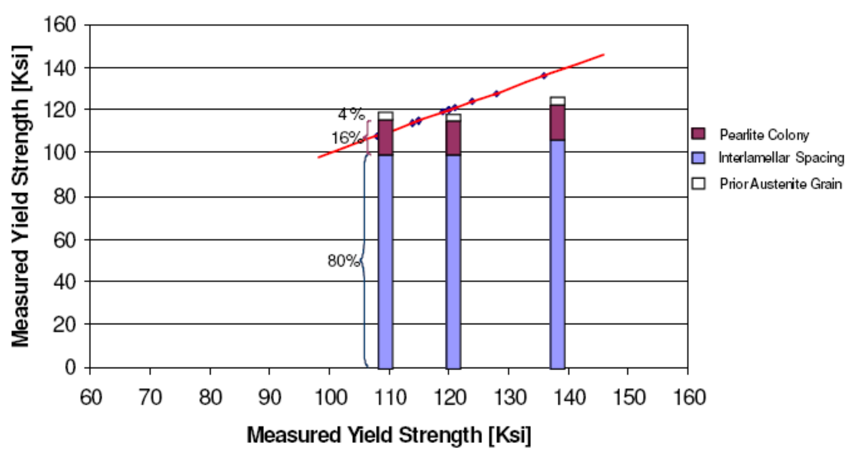

Figure 5. The bar height represents the total contributions of microstructural factors to the yield strength of rail steels.

In general, most equations to describe the contributions to strength includes [8] the resistance to dislocation motion, the Peierls-Nabarro stress, solid solution strengthening, interlamellar spacing, pearlite%, pearlite colony size and dislocation cell size.

The presence of pro-euctectoid cementite was observed in some of the commercial rail steels. It was found decorating the prior austenite boundaries. Evidence of the pro-eutectoid cementite in premium rail steels is shown in Figure 6.

A summary of the major microstructural features found in the commercial rail steels is illustrated in Figure 7. These microstructural factors are believed to be responsible for the performance of rail steels. One of the most important observations in this part of the work was the presence and effect of pro-eutectoid cementite and its well-recognized damaging effect on wear and rolling contact fatigue.

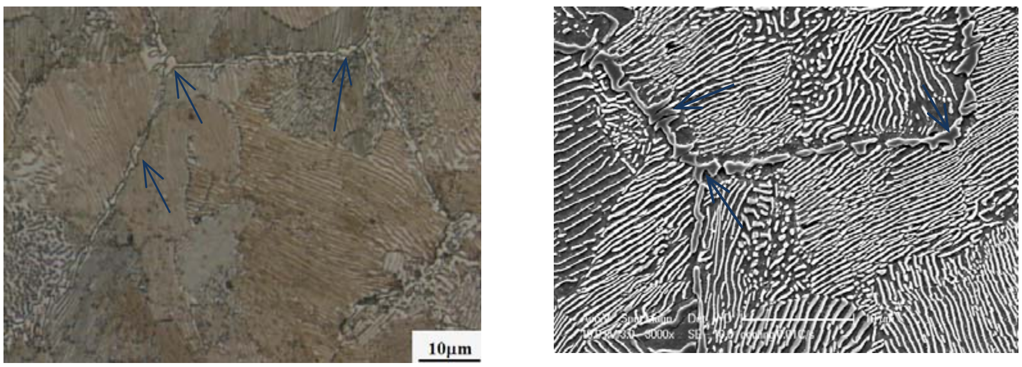

Figure 6. Optical and SEM micrograph showing the presence of pro-eutectoid cementite in a rail steel sample.

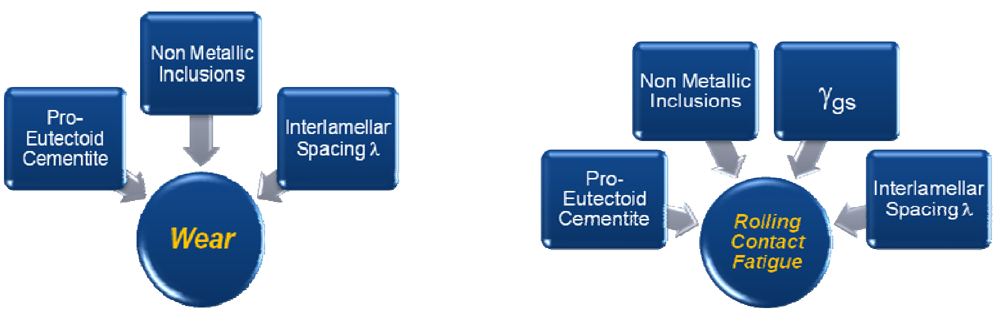

Figure 7. Main microstructural factors responsible for the performance of rail steels, where γ_{gs} is the austenite grain size.

Based on the microstructural observations obtained in the first phase of this work and coupled with the wear performance of the premium rail steels provided by the Transportation Technology Center, a linear relationship was developed as –shown in figure 8. The wear factor in figure 7 is strongly related to a series of microstructural factors, i.e., the type, size and volume fraction of non-metallic inclusions, the matrix hardness, the volume fraction of pro-eutectoid cementite and the microstructure (specially the interlamellar spacing).

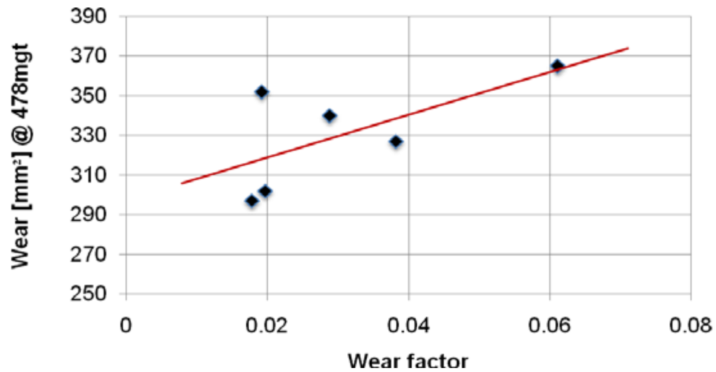

Figure 8. Relation between the wear behavior of rail steels and microstructural factors.

Results from experimental new rails

Prior to the thermomechanical studies, samples from each laboratory heat were reheated in a furnace under a controlled atmosphere, in order to develop the initial austenite grain size of 200µm. The condition used to develop the austenite grain size are shown in Table 5.

Table 5. Prior austenite grain size and reheating temperatures used in each steel

	Reheat T, ^{o}C	Austenite grain size, µm
Rsteel1	1160	208 ± 25
Rsteel2	1200	211 ± 42
Rsteel3	1155	203 ± 18
Rsteel4	1210	215 ± 16

A series of systematic thermomechanical studies was done on each experimental steels. Variations deformation levels, cooling rates as well as cooling paths were explored. All the samples generated from this systematic study were microstructurally assessed; hardness evaluation was also performed in all samples. Figure 9 shows the pearlitic microstructure obtained with the thermomechanical experiments. From these results and based on the AREMA requirements, the rolling conditions of Table 2 were selected. From those samples which exhibited full pearlitic microstructure, the interlamellar spacing was evaluated and compared with the hardness obtained as illustrated in Figure 9e.

From the results of the TMP experiments, the rolling conditions were determined (Table 2). The laboratory heats were rolled on a laboratory hot rolling mill. The microstuctural analysis was performed from the samples after the rolling. The hardness of the as-hot rolled plates was also evaluated, the final microstructure and hardness of the as-rolled plates is shown in Table 6.

The hardness results shown in Table 6 indicates that three out of four steels reached or exceeded the AREMA target value (38 HRC). Figure 10 shows a comparison of the hardness values from commercial premium rail producers and the hardness values of the experimentally developed steels.

Table. 6. Hardness and microstructure obtained from hot rolling.

	Rsteel 1	Rsteel 2	Rsteel 3	Rsteel 4
Microstructure	Pearlitic	Pearlitic	Pearlitic	Pearlitic
Hardness [Rc]	40.4	43.1	36	38

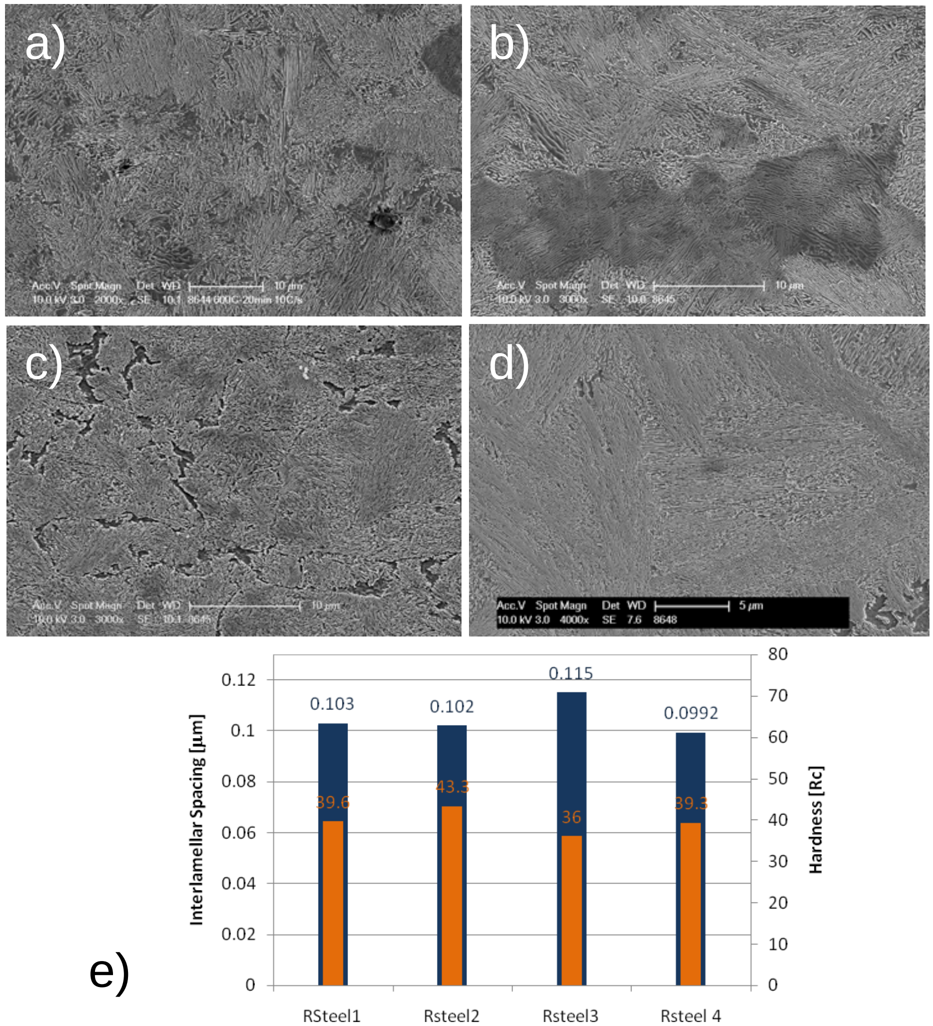

Figure 9. Microstructure obtained a) Rail steel 1, b) Rail steel 2, c) Rail steel 3 and d) Rail steel 4.e) Interlamellar spacing and hardness obtained.

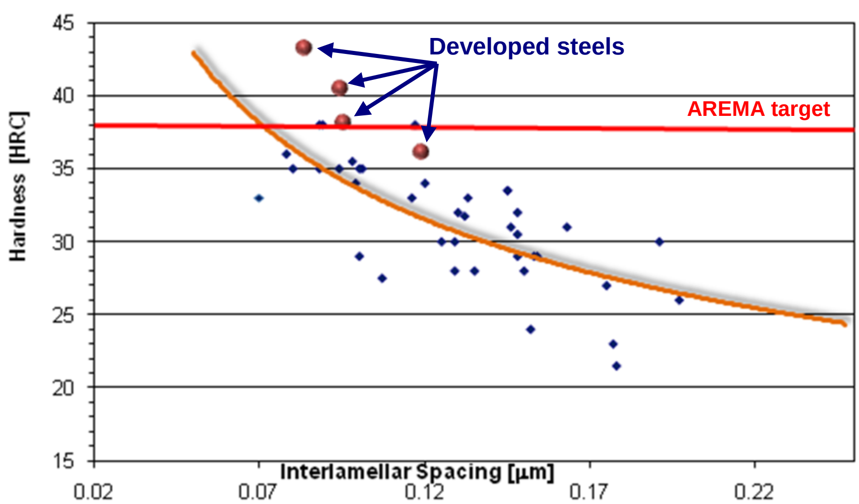

Figure 10. Hardness values of premium rail and the developed steels

Rail steels 1, 2 and 5 (those which complied and/or exceeded the AREMA hardness target) were selected for tensile property evaluation. The tensile results are shown in Table 7. It is clear that all the samples meet the AREMA target, however rail steel 2 exceed by more than 30% the AREMA target for yield strength It should also be noted that the elongation obtained in rail steel 1 which exceed by 50% the AREMA target for elongation.

Table 7. Tensile test values of rail steels developed by this research.

Producers	Yield Strength, ksi	Tensile Strength, ksi	Difference	Elongation, %
Rsteel 1	134.9	188.4	53.5	20.4
Rsteel 2	158.9	211.7	52.7	13
Rsteel 5	122.9	182.0	59.2	14.2
AREMA target	**120**	**147**	**-**	**10**

Figure 11 shows a comparison of yield strength and elongation values from commercial premium rail steels and the yield strength from the rail steels developed in this research.

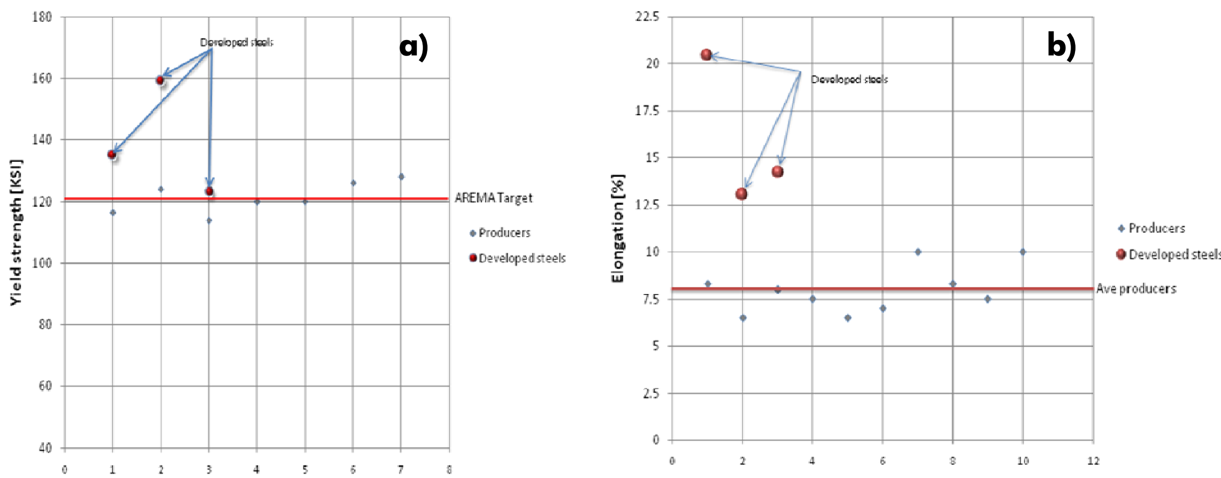

Figure 12. Comparison of a) Yield strength and b) Elongation between premium rail steels and the developed rail steels.

Conclusions

A thorough assessment of the microstructural features of current premium rail steels was conducted to understand the microstructural factors that are important in controlling the performance of rail steels. It was found that the performance of rail steels, i.e. rolling contact fatigue (RCF) and wear are strongly dependant on a complex system involving several microstructural factors. In the open literature it was clearly established that two of the major microstructural factors affecting negatively RCF and wear were the presence of non-metallic inclusions and the interlamellar spacing. In the present work was found that also the presence of pro-eutectoid cementite and the prior austenite grain size play also an important role on controlling RCF and wear. Based on the knowledge acquired in microstructural assessment, and by applying modern concepts of alloy and process design, three new steels were developed that were shown to be very successful in terms microstructure, properties and performance. The results from this work guideline in terms of chemical composition, austenite conditioning through TMP and transformation control were developed to design of high performance heavy haul rail steels for the 21st Century.

Acknowledgements

The authors would like to express their gratitude to Transportation Technology Center Incorporated (TTCI) for their invaluable support and thank to BAMPRI and its supporters .

References

[1] K. Sawley and J. Kristan, "Development of bainitic rail steels with potential resistance to rolling contact fatigue", *Fatigue & Fracture of Engineering Materials & Structures,* Vol. 26, No.10 (2003), 1019–1029.

[2] D.F.Cannon and E.O.Edel, "Rail Defects: An overview," *Fatigue & Fracture of Engineering Materials & Structures,* No.10 (2003), 865-886.

[3] M. Ueda et al., Development of hypereutectoid steel Rails for Heavy Haul Railways. *6th International Heavy Haul Railway Conference,* Cape Town, (1997).

[4] Yong-Jin Park and I.M. Bernstein, "Mechanism of Cleavage Fracture in Full Pearlitic 1080 Rail Steel," *Rail Steels-Developments, Processing and Use, ASTM STP 664*, (1978), 287-302.

[5] Maria das Graças Mendes da Fonseca Gomes, Luiz Henrique de Almeida, Luiz Claudio F. C. Gomes and Iain Le May, "Effects of Microstructural Parameters on the Mechanical Properties of Eutectoid Rail steels," *Materials Characterization*, Vol. 39, No. 1 (1997), 1-14.

[6] J.M. Hyzak and I.M. Bernstein, "The Role of Microstructure on the Strength and Toughness of Fully Pearlitic Steels," *Metallurgical Transactions A*, Vol. 7A, No.8 (1976), 1217-1224.

[7] P. Clayton and D. Danks, "Effect of Interlamellar Spacing on the Wear Resistance of Eutectoid Steels under Rolling/Sliding Conditions," *Wear,* Vol. 135, (1990), 369-389.