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Properties and microstructure of high performance wheels

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ABSTRACT

The methodology followed by Transportation Technology Center, Inc., to develop a pearlitic high performance wheel steel (identified as SRI) is described in the first part of this paper. Ideally, this steel will be proposed as high performance wheel steel to the Association of American Railroads (AAR). If successful, the SRI steel will be identified as AAR Class D steel. The second part of the paper provides the results of the mechanical testing of seven high performance wheels (six pearlitic and one bainitic) manufactured by different companies and are compared to the SRI steel. Some of these high performance wheel steels had been tested in heavy haul lines, but had not been tested in the USA heavy haul environment. The results in this paper indicate that the mechanical properties of the SRI steel are superior to those of AAR Class C steel. Vacuum degassing can significantly improve fatigue resistance and is recommended for the SRI steel. The experimental SRI wheels were forged in Brasil at the MWL Brasil facilities. The cleanliness and mechanical properties of the SRI wheel steels compared to the other high performance wheel steels show that among the pearlitic steels, the SRI steel has the highest cleanliness and mechanical properties.

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1. Introduction

For the last few decades, wheel and axle loads in heavy haul lines have increased considerably. In contrast, wheel development has not been improved accordingly and has resulted in a change in wheel failure mode from wear to fatigue related issues [1]. This can be understood as an increase in the number of wheels that are removed prematurely. Recently, the Transportation Technology Center, Inc. (TTCI) proposed a new Strategic Research Initiative (SRI) to develop a new high performance wheel steel. The initiative includes testing of high performance wheels from domestic and international producers. TTCI identified mechanical properties and cleanliness as the major factors required to improve wheel performance and to extend wheel life. There are two main routes to improve mechanical properties: chemical and thermomechanical. Rail manufacturers have, until now, explored the chemical route with relatively good success. TTCI and wheel manufacturers have followed similar approaches in the development of high performance wheels. TTCI has developed a new high performance steel identified as SRI wheel steel. The wheels were manufactured at the MWL Brasil facilities.

Research has shown that the presence of non-metallic inclusions (particularly the hard ones such as alumina (Al_2O_3) and complex oxides) and voids has detrimental effects on mechanical properties of steels [2]. Preliminary attempts to determine the critical particle size having detrimental effects on wheel steel performance indicate that inclusions of 1 mm^2 (1.6E^{-3} in.^{2}) or larger can reduce wheel performance [3]. Previous attempts to demonstrate the effect of steel microcleanliness on fatigue performance of railroad components have been published [4–14]. More recent work using the Murikami–Endo model [2] demonstrated that the common defects (non-metallic inclusions and pores) identified in wheel steels can contribute to a reduction of up to 20–25% in the endurance limit of the steel [6,7]. The analysis was conducted using cleanliness results from actual wheels removed from service based upon image analysis and ASTM procedures [4,5]. Using the same approach, it was determined that particles with a diameter of 10 μm (3.9E^{-4} in.) or more can be detrimental to the integrity of wheels [7]. Using a more sophisticated methodology, it was determined that the critical particle size that can adversely affect the performance of wheel steel has an approximate diameter of 30 μm [8,9]. Although there are some discrepancies in the above determinations, it is clear that all cases demand cleaner steels.

2. Background

2.1. Advanced wheel steel development

AAR Class C steel is commonly used for general freight and heavy haul freight services. Fig. 1 shows an example of a typical casting defect (shrinkage pore or void) on the microstructure of a wheel that was removed prematurely from revenue service due to exces-

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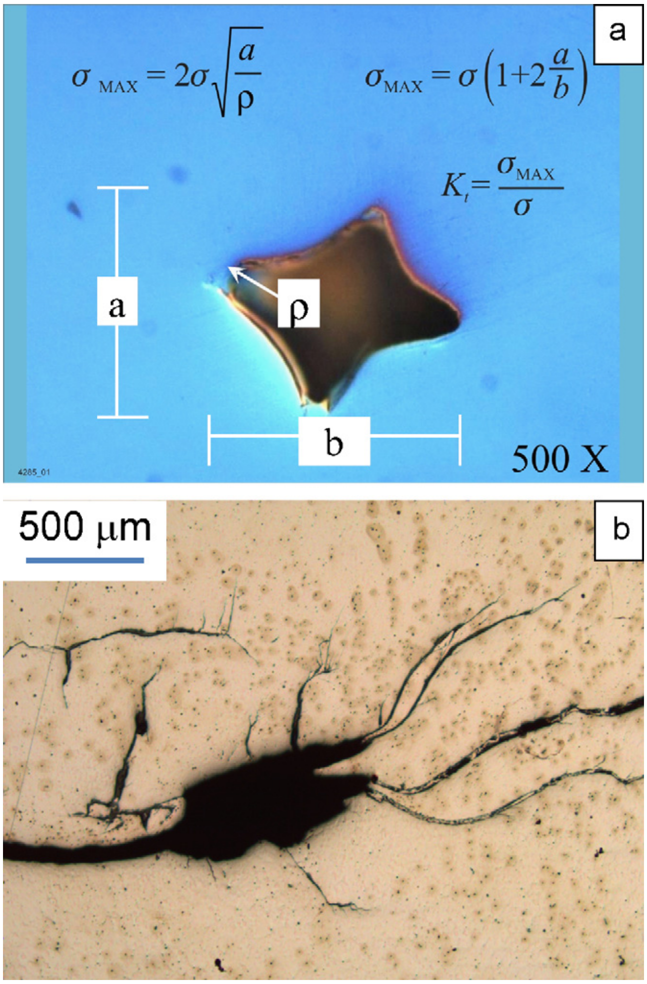

Fig. 1. (a) Effect of a pore on stress intensity (K_t), equations showing the effect of shape and size on K_t and (b) shelling initiation at a pore present near the surface of a Class C wheel removed from service due to excessive shelling.

sive shelling. The pore in Fig. 1a is relatively large and was found away from the location with severe shelling, but near the tread surface <1 cm (0.39 in.). The pore shown in Fig. 1a is used to demonstrate the stress intensity factor equations given in the same figure. Fig. 1b shows the actual stress intensity factor effects at pores and

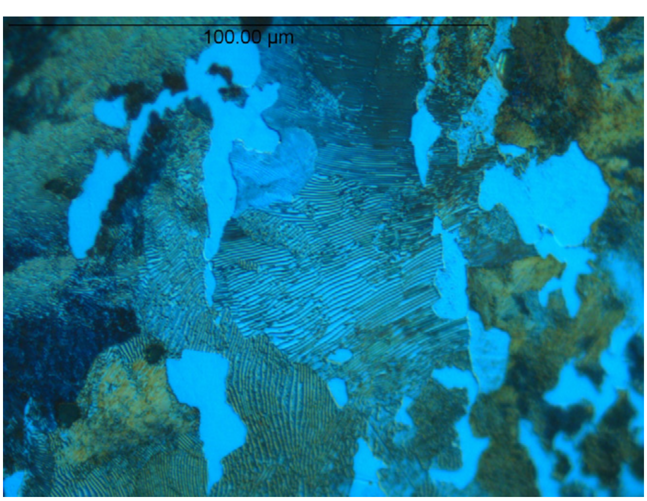

Fig. 2. Pearlitic microstructure with low amount of inclusions of one of the experimental steels.

how they promote shelling. The equations included in Fig. 1 outline the effect of the size and the curvature of defects on the stress intensity factor (K_t). K_t is a parameter used to measure the number of times an applied stress is concentrated at a defect location. In other words, this represents the number of times a material (e.g. wheel steel) is weakened by the presence of defects. The main material properties affected by the presence of such defects are strength and endurance limit. Unfortunately, the equations in Fig. 1 do not take into account the effects of distribution and nature of the defect among other parameters that further reduce fatigue performance and wheel life.

It is expected that wheel life can be increased by designing steels with improved mechanical properties. For instance, the simplest and most effective way to improve wear performance on rails is using harder steels [14]. Excessive amounts of alloying elements (e.g. carbon) can be detrimental and can result in undesirable levels of pro-eutectoid cementite along the prior-austenitic grain boundaries. However, some steel manufacturers had successfully suppressed the precipitation of pro-eutectoid cementite by the additions of key elements and more recently, by optimizing the thermomechanical processing. It is expected that this will reduce crack formation and will extend, fatigue life (e.g. rolling contact fatigue (RCF)), elongation and fracture toughness [14]. For this reason, the proper combination and amount of key alloying elements (e.g. Mo, V, Nb, Mn, etc.) are of great importance and can result in the proper optimization of the mechanical properties of newly designed steels (e.g. SRI). However, alloying elements in excess (e.g. Mo and C) can also degrade mechanical properties and can compromise the integrity of railroad components. Therefore, advanced steel design is of paramount importance.

This work presents test results for the SRI steel developed by TTCI. Additionally, the mechanical properties test results for seven high performance wheels manufactured by different companies are presented and compared to the SRI steel. Each manufacturer donated a heat of high performance wheels for a total of more than 500 test samples. This paper briefly describes the current high performance wheel test being conducted under an extreme environment produced at the Facility for Accelerated Service Testing (FAST) at TTC and in North American heavy haul service, which will help identify a new steel that can extend wheel life considerably. If the SRI steel is determined to be the best, then this composition will be proposed to the AAR as the next generation high performance wheel steel (Class D steel). The following wheel manufacturers are participating in the testing:

- Griffin;
- Lucchini (wheels previously tested in international (Lucchini, Sweden; OneSteel, Australia) heavy haul lines. OneSteel wheels were tested in the BHP Billiton line with axle loads of ∼44 tonnes);
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- Standard Steel;
- Sumitomo;
- Valdunes;
- SRI;

3. Experimental procedure

Tensile testing was conducted at temperatures varying from −40 °C (−40 °F) to 538 °C (1000 °F) following ASTM standard procedures to imitate winter and an excessive breaking temperatures observed in heavy haul lines across North America. Tensile testing was performed in accordance with ASTM E8-00 [15]. Three specimens per experimental steel (SRI) as well as for each wheel type

Table 1
Preliminary mechanical test results of the experimental SRI steels and the AAR Class C steel.

Wheel steel	Yield (ksi)	UTS (ksi)	Elongation (%)	Hardness (HB)
AAR Class C[a]	76.6	146.5	19.1	302
AAR Class C	71.9	139.2	16.1	302
SRI Exp.-1	67	139	16.1	277
SRI Exp.-2	73.1	139.4	17.2	285
SRI Exp.-3[b]	98	149.8	19.7	302

[a] Class C vacuum treated.
[b] Best SRI (candidate) steel, the mechanical properties will vary for the actual wheels once the heat treatment is optimized.

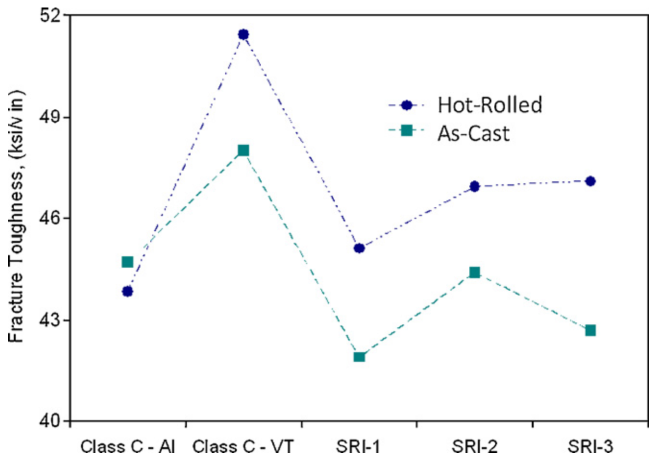

Fig. 3. Results of fracture toughness tests for the as-cast and hot-rolled plate samples. Al and VT stand for aluminium killed and vacuum treated.

were tested at room temperature. Fracture toughness testing was conducted as per the ASTM E399 [16] standard at room temperature. Brinell hardness testing was conducted as per indicated by the AAR and the E10-08 ASTM standard [17]. The cleanliness analysis of the wheel steels was conducted using the method developed by BNSF Railway [14]. This method involves the E-45 and E-1245 ASTM standards [4,5]. The sample's microstructures were prepared by following conventional grinding and polishing procedures.

4. Alloy development

In order to identify a chemical composition that can satisfy the demands of the North American heavy haul environment, three experimental short heats (68 kg (150 lb)) of three different chemical compositions were cast. The as-cast ingots were heat treated

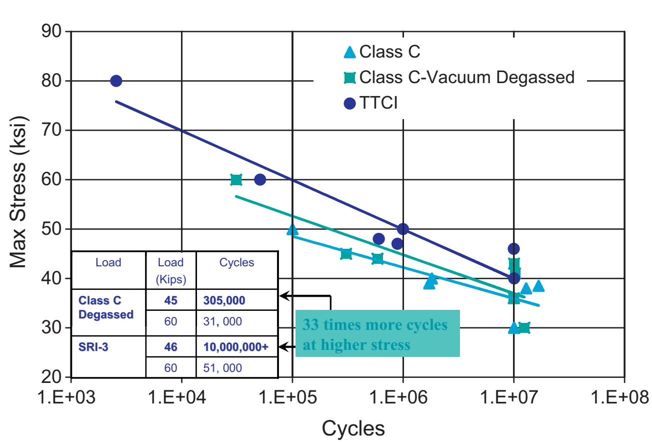

Fig. 4. Fatigue results of AAR Class C and SRI-3 steels.

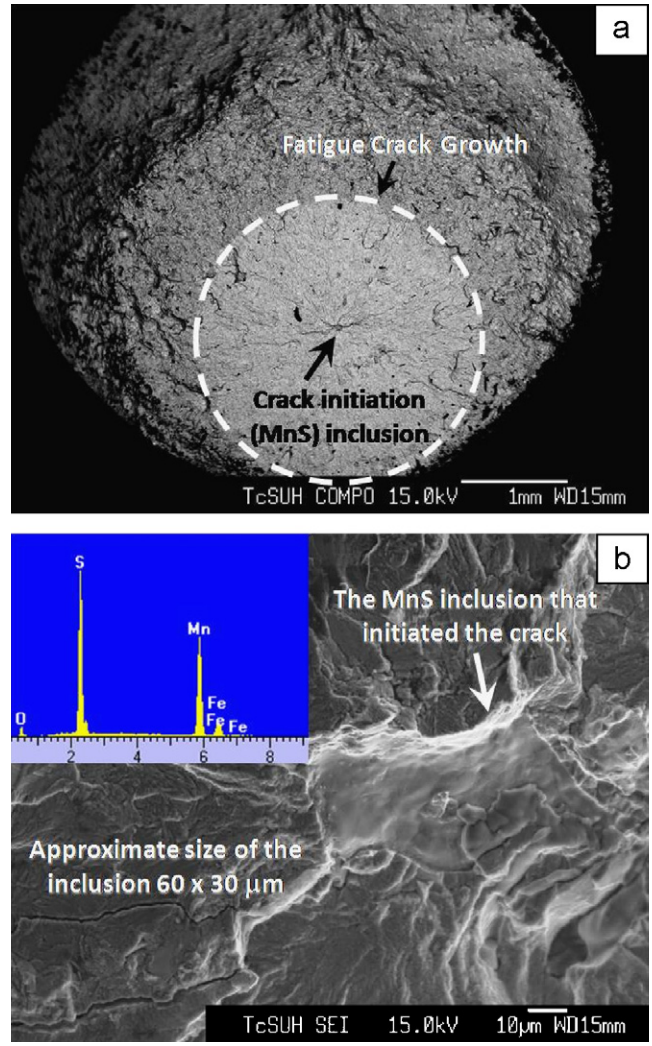

Fig. 5. Crack surface of a Class C wheel sample tested under uniaxial fatigue (a) fracture and (b) MnS inclusion that Initiated the failure.

and hot rolled to simulate typical wheel manufacturing processes. The as heat-treated and as-forged samples were used for mechanical testing. Along with the experimental compositions, two ingots (68 kg (150 lb) each) of AAR Class C steel were cast. One ingot was produced using the conventional aluminium-killed method and the other one was produced using vacuum treatment conditions. The AAR Class C ingots were used as a baseline to identify the experimental steel with superior mechanical characteristics, leading to improved performance in service. All AAR Class C and SRI ingots were cast under the same conditions except for the ingot cast under aluminium-killed conditions. The aluminium-killed ingot was cast to demonstrate that vacuum degassing can increase mechanical properties, particularly fatigue related properties. Following this process permitted a direct comparison of the mechanical properties of the current AAR Class C steel and the experimental steels.

In addition to the vacuum treatment, the experimental steels were designed using low levels of sulfur (0.001 wt%) and phosphorus (0.007 wt%) to reduce microstructural defects (voids and non-metallic inclusions) as possible. The chemical composition ranges for the SRI steels are presented in Refs. [18,19]. This is directly reflected in a superior microcleanliness of the experimental steels, as compared to the AAR Class C steel. In theory, this will make the experimental steels more fatigue resistant (e.g. shelling). Fig. 2 shows a micrograph of one steel as obtained from the experi-

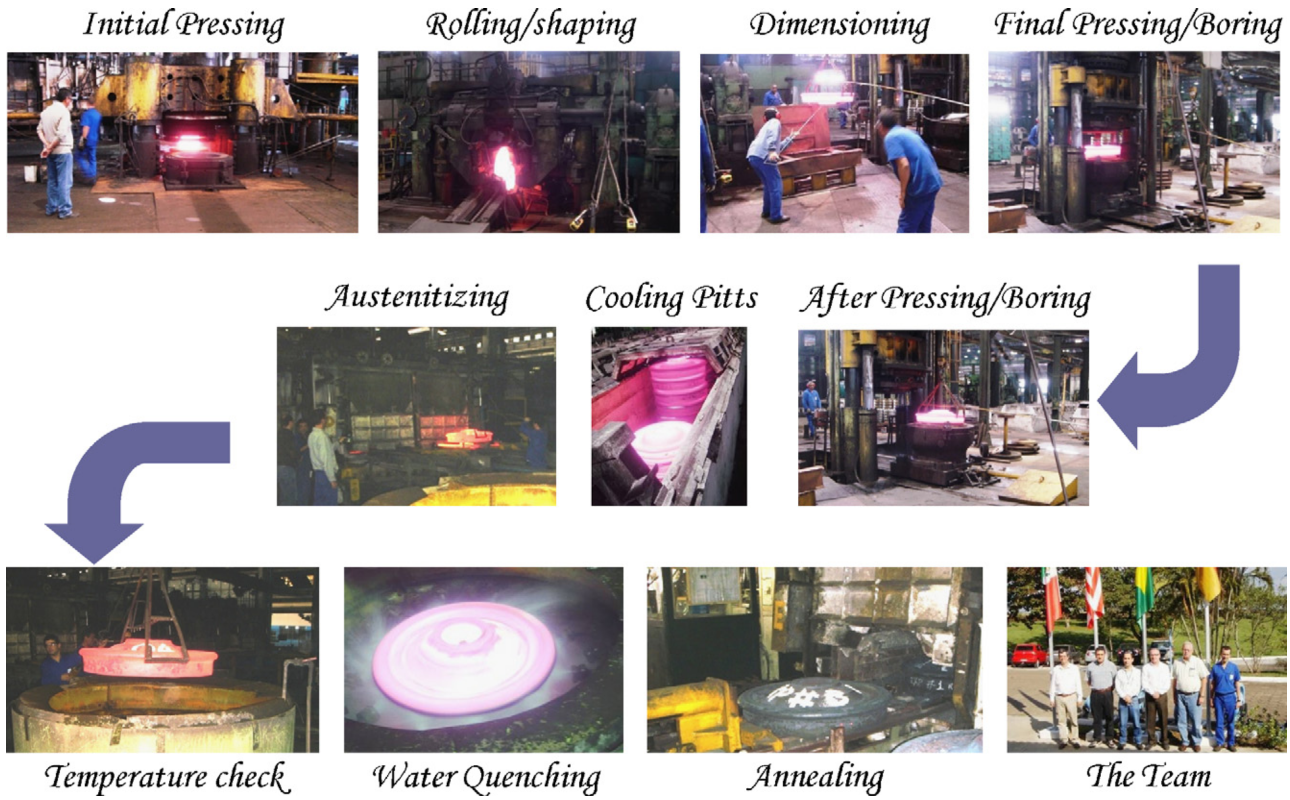

Fig. 6. MWL Brasil forging and heat treating for the SRI Wheel steels.

mental ingots in the as-rolled and heat-treated condition. All steels were heat treated prior to the mechanical testing; the heat treatment process included heating the ingots at 815 °C (1500 °F) for 1 h followed by a rapid air cooling to 482 °C (900 °F) and tempering for 1 h followed by a cooling to room temperature under normal heat exchange conditions. This heat treatment was selected based on the common practice followed by some AAR Class C wheel manufacturers.

Fig. 2 shows the presence of pearlite with traces of hypoeutectoid ferrite along the prior-austenite grain boundaries. The reason for this combination of phases in the microstructure is to have the advantage of the well known high wear resistance of pearlite [14,20] and to prevent the formation of pro-eutectoid cementite along the grain boundaries. This may increase fracture toughness and reduce crack propensity along the grain boundaries and ideally shelling.

The experimental steels were tested in the as-cast and hot-rolled condition. The results of the mechanical testing indicate that the experimental steels have comparable or superior mechanical properties as compared to AAR Class C steel (Table 1 and Figs. 3 and 4) in both the as-cast and hot-rolled conditions. Table 1 lists the preliminary results of the tensile and hardness tests of AAR Class C steels and three SRI experimental steels. It is important to mention that the heat treatment conditions were not optimized for the experimental steel plates, because the objective of this portion of the work was to directly compare the mechanical properties of the experimental steel to AAR Class C steel. Nonetheless, it is important to point out that the heat treatment for all steels was identical. The optimization of the heat treatment conditions was conducted for the actual wheels produced using the experimental steel at the MWL Brasil facilities and is discussed in later in this paper.

Figs. 3 and 4 show the benefits of vacuum treatment and clearly indicate that vacuum treatment considerably increases fracture toughness and fatigue life. The AAR Class C steel had significant mechanical properties improvements when cast under vacuum degassing conditions. The steel SRI-1 has lower tensile properties than the AAR Class C steel that is opposite to the SRI-2 steel that has slightly higher tensile properties. However, the SRI-3 (in this paper identified as SRI) steel has noticeably better mechanical properties comparable elongation than the vacuum degassed AAR Class C steel. But, the SRI steel had higher elongation results than the aluminium-killed AAR Class C steel.

Based upon these results, the SRI-3 steel was selected as the best candidate composition for the experimental high performance wheel steel. The benefits of vacuum degassing for the SRI steel can be observed as a further enhancement of the mechanical properties of the SRI steel over AAR Class C steel.

Fig. 4 shows that the fatigue performance of the SRI steel is the best when compared to the AAR Class C steel cast under aluminium killed and vacuum treated conditions. Furthermore, comparing the fatigue results of the two AAR Class C steels demonstrates the benefits of vacuum degassing (cleanliness). These test results confirm that microstructure defects (porosity and non-metallic inclusions) play an important role in fatigue performance. The effect of defects of the fatigue performance of the steel is further amplified by the nature of the inclusion such as size and distribution among other factors. For instance, larger defects affect fatigue resistance more than smaller defects do. Therefore, it is expected that the SRI steel will result in superior wheel performance due to its higher mechanical properties and in particular, its improvement in fatigue performance.

Ideally, the fatigue improvements will reduce shelling and vertical split rims, and is in agreement with previous reports [2,3,7–13]. Unfortunately, all these publications report values based on numerical simulations and there is not sufficient data results for multi-axial fatigue to support/demonstrate the effect of inclusions on steel performance. The critical particle size under multi-axial fatigue conditions has not been demonstrated. Fig. 5a

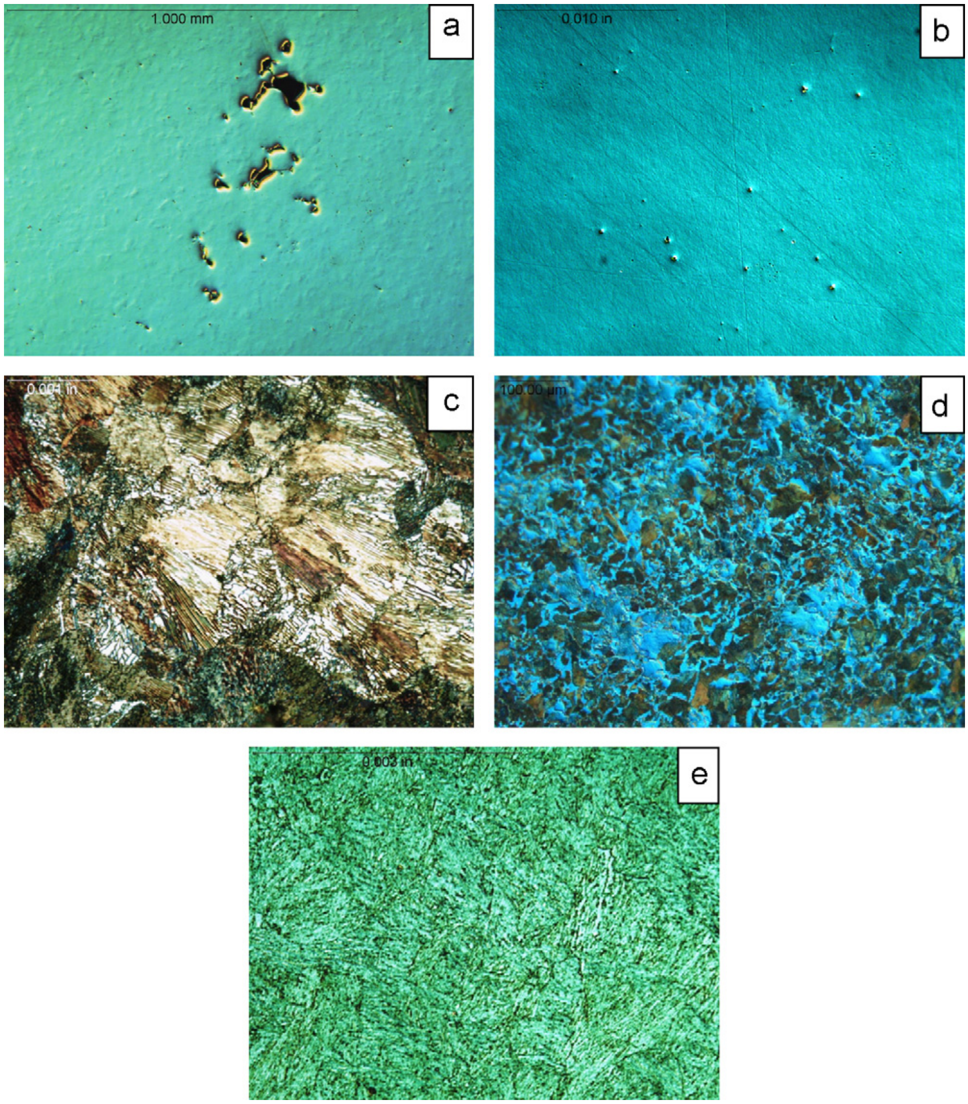

Fig. 7. Microstructures of AAR Class C wheel steel (a and c), SRI wheel steel (b and d) and bainitic wheel steel (e), in as-polished (a and b) and as-etched (c–e) conditions.

and b is a stereograph and a SEM pictures of an AAR Class C steel tested under uni-axial fatigue conditions showing the crack initiation and its respective composition (manganese sulfide (MnS)).

Based on these results, the SRI steel was selected to cast a heat of steel (45 metric tonnes) to produce experimental high performance wheels. The experimental SRI wheels were forged and heat treated at MWL Brasil facilities. The mechanical testing results of the SRI steel are compared to other high performance wheels from different manufacturers. Fig. 6 shows a schematic representation of the steps followed at MWL facilities for forging and heat treating the SRI steel.

5. High performance wheels

5.1. Analysis of the microstructure

Fig. 7 shows examples of the microstructures of selected test wheels in as-polished (a and b) and as-etched (c–e) conditions. Fig. 7a and c is examples of AAR Class C wheel steel for comparative purposes. Fig. 7b, d, and e is microstructures of the high performance wheels. Fig. 7b and e shows the higher cleanliness of some of the test wheels as compared to AAR Class C wheel steel. The superior microstructure refinement of the SRI wheel steel is shown in Fig. 7d (compare with Fig. 7c) showing finer pearlite and traces of hypo-eutectoid ferrite. Fig. 7e shows the microstructure of a bainitic wheel steel. The microstructure of all other high performance wheel steels is pearlitic.

5.2. Tensile test results

Fig. 8 shows the results of the tensile test properties conducted between −40 °F and 1000 °F and includes: ultimate tensile strength, yield strength, and percent elongation at failure. A value of 900 MPa was pre-selected as a minimum value for the next generation of Class D wheel steels by TTCI/AAR. The complete Class D steel specification and exact values will be determined based on the results of the ongoing revenue test. Only three of the wheel steels met yield strength equal or higher than 900 MPa (∼130 ksi). The yield strength of the rest of the wheel steels is comparable to AAR Class C wheel steel. It is important to note that the higher yield strength of Wheel 6 is attributed to its microstructure. In the room temperature testing Wheels 5, 6 and SRI meet the minimum yield strength requirements for the premium wheels or Class D steel. All wheels show a reduction in yield and tensile strength as a function of temperature. The opposite effect is observed for elongation, it means elongation increases as a function of temperature except for the

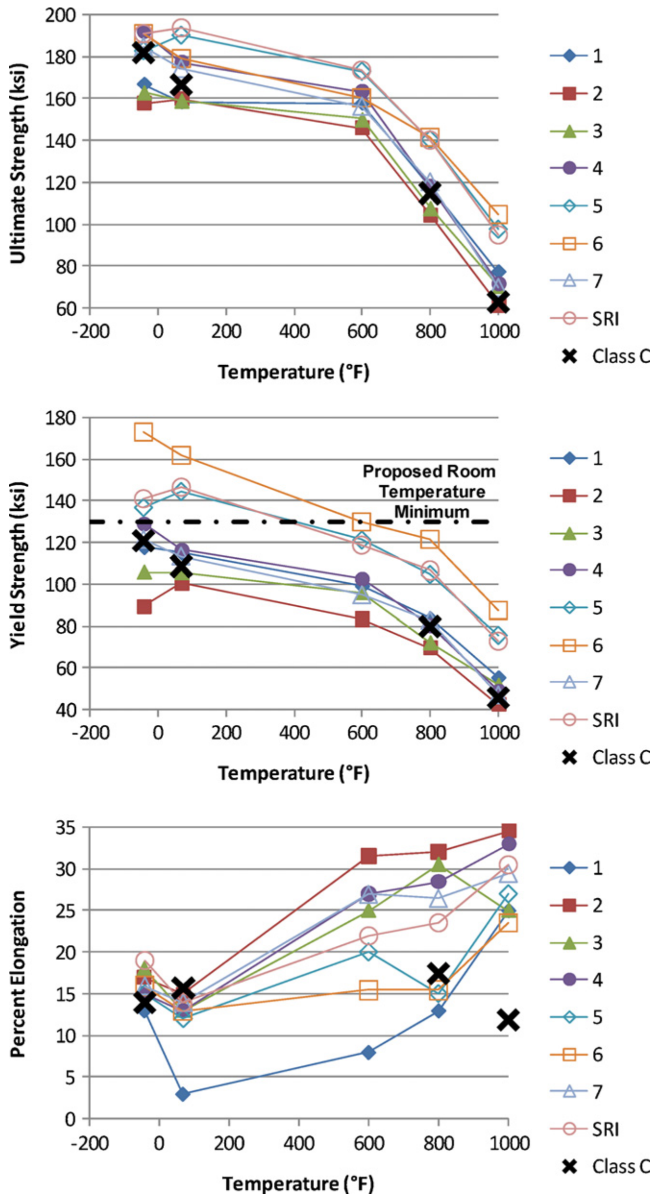

Fig. 8. Summary of the tensile properties for high performance and AAR Class C wheels (values for AAR Class C at 800 °F and 1000 °F[21]).

Class C wheel. In the traditional school of thought it is usually known that the increasing in strength has a trade off in elongation that is not necessarily the case for Wheel 5 and SRI.

5.3. Cleanliness

The BNSF cleanliness analysis requires the analysis of six metallographic samples. The cleanliness results in Fig. 9 indicate that Wheels 1, 2, 6, 7, and the SRI wheel steel met the proposed minimum cleanliness requirements. Values above the dashed or dotted lines did not meet the proposed cleanliness requirements.

5.4. Hardness

Fig. 10 shows the average hardness values of the high performance wheel steels and AAR Class C wheel steel taken in three different locations along the wheel tread. Wheels 2, 6 and 8 have hardness between 362 and 368 HB, Wheels 1, 4, 5, 7 and SRI showed hardness between 396 and 411 HB and Wheel 3 has a hardness

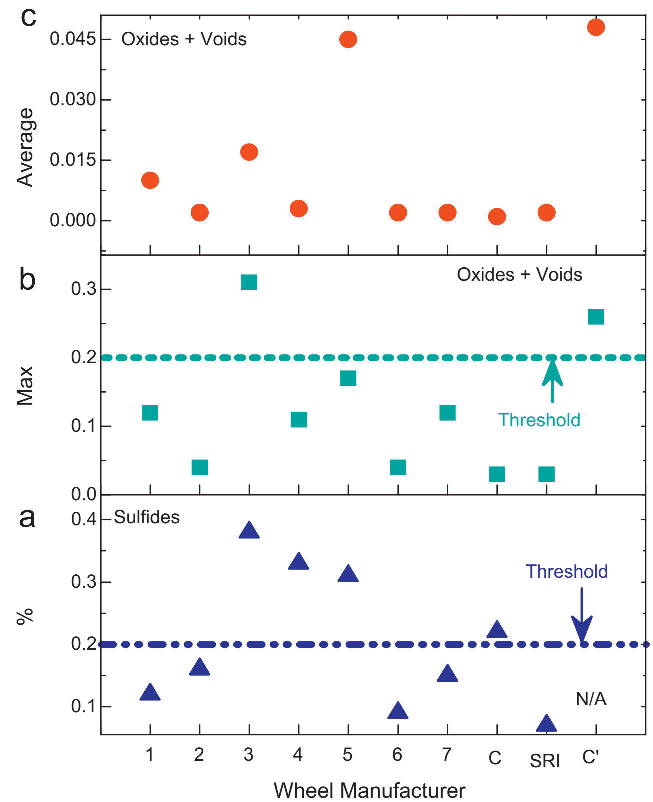

Fig. 9. Summary of cleanliness results, (a) sulfides (%), (b) oxides + voids (max) and (c) oxides + voids (avg). Wheels labeled as 8, 9 and 10 correspond to: AAR Class C, SRI and median value of 40 AAR Class C′ Wheel 1, respectively.

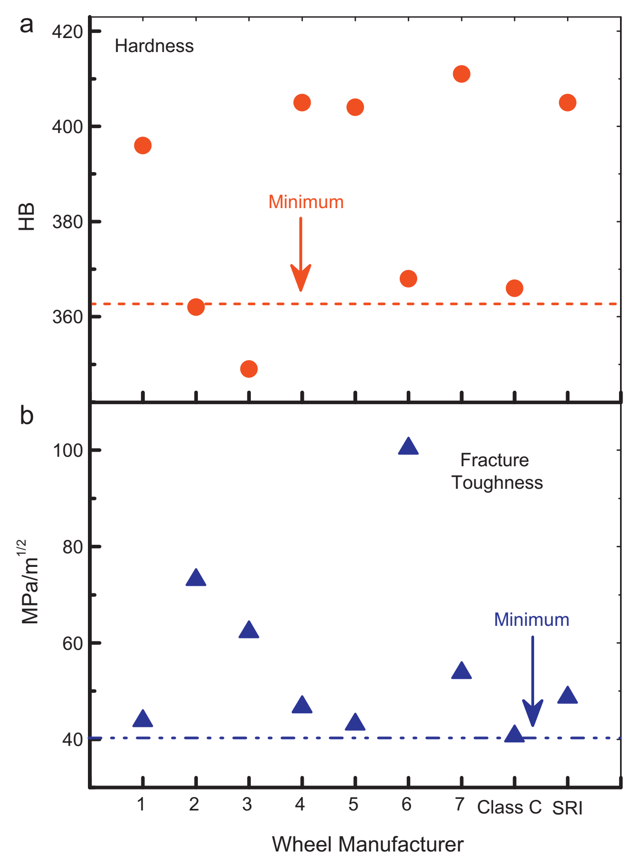

Fig. 10. Results of fracture toughness test conducted at room temperature. Wheels labeled as 8, and 9 correspond to: AAR Class C, and SRI, respectively.

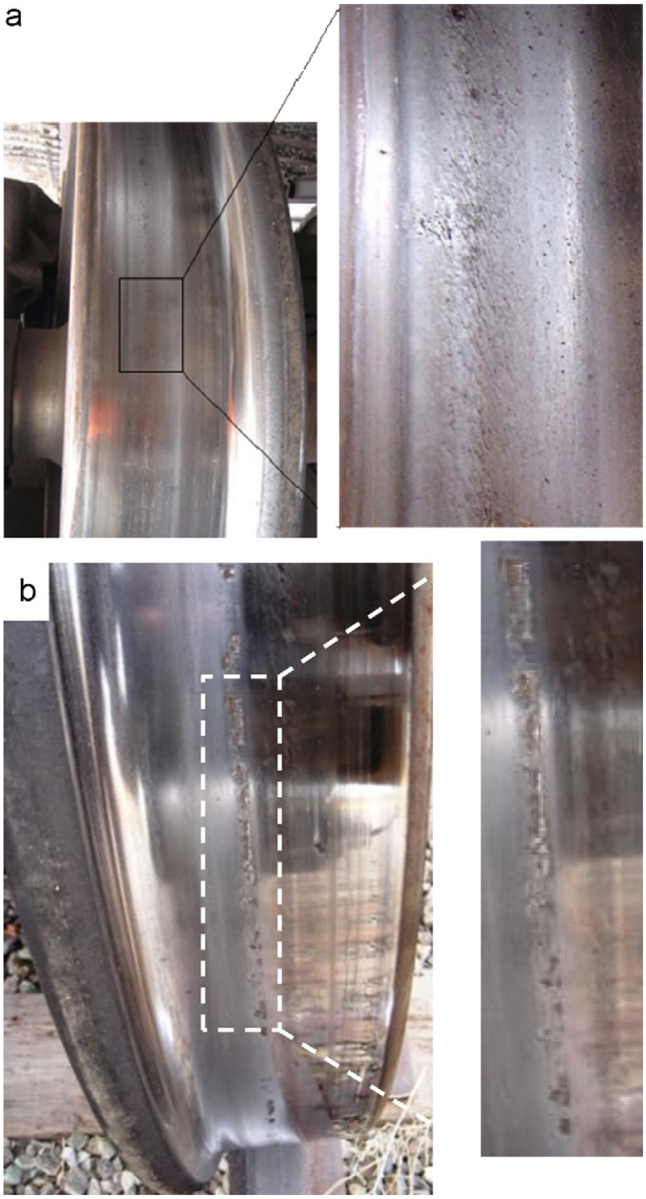

Fig. 11. Picture from high performance wheels tested at FAST (durability and braking tests) showing (a) rolling contact fatigue and (b) shelling.

of 349 HB. All wheels meet the minimum hardness requirements for the Class D wheels steel (363–400 HB) except Wheels 2 and 3. Although, the hardness of Wheel 2 (362 HB) can be considered along the minimum requirements for Class D premium wheel steel.

5.5. Fracture toughness

Fig. 10 shows the results of fracture toughness tests for the high performance and AAR Class C wheel steels. Fig. 10 shows that at room temperature, all high performance wheels have fracture toughness values above AAR Class C (40 MPa/m$^{1/2}$) wheel steel and meet TTCI's proposed minimum fracture toughness for high performance steel. Wheels 1, 4, 5, 7 and Class and SRI have fracture toughness between 40 and 54 MPa/m$^{1/2}$, while the fracture toughness of Wheels 2, 3 and 6 is between 62 and 100 MPa/m$^{1/2}$.

The traditional school of thought says that as the hardness increases fracture toughness decreases. This relation is observed by comparing the results of hardness and fracture toughness for Wheels 2, 3 and 6 (high fracture toughness) on one side and the rest of the wheels (lower fracture toughness). However the results reported in Fig. 10 do not necessarily present a trend, particularly the Class C wheel.

6. Ongoing tests

As of today the test wheels have been installed under 130,000- and 143,000-kg cars for initial performance testing at revenue service and FAST. At FAST the wheels have been tested under excessive braking and for durability. Fig. 11 shows examples of the surface characteristics of some wheels. Some slight differences can be seen for the high performance wheels. It is still too early to draw conclusions based on these differences and laboratory results presented herein. The revenue service test cars operate between Wyoming's Powder River Basin and the power plants served by the Union Pacific Railroad. The results of the full scale testing (FAST and revenue service) will reveal detailed information to set metallurgical and non-metallurgical requirements for the AAR Class D wheels; it is expected that this will occur in 2012.

7. Conclusions

The selected SRI steel showed superior mechanical properties when compared to the commercial AAR Class C steel. Vacuum degassing showed improvements in the mechanical properties of the AAR Class C steel and it is then expected that such improvements may also be observed for the SRI steel. The overall quality and characteristics of the eight high performance wheels were satisfactory. The microstructural examination indicated that all wheels but one were primarily composed of pearlite. One test wheel was composed of a bainitic microstructure. Only the SRI and steel 6 met all of the proposed requirements for high performance wheel steel. The room temperature yield strength of three of the eight test wheels was greater than 130 ksi. The surface hardness values for five of the eight test wheels were in the range of 380–420 HB. Five out of the eight test wheels met the proposed cleanliness standards for advanced wheel steels. All of the test wheels had room temperature fracture toughness values greater than AAR Class C wheel steel.

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