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Steel Development for High Performance Wheels

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Summary

Recent findings indicate that in order to improve wheel life, microcleanliness and mechanical properties of the wheel steel require considerable improvement. Based on laboratory test results, Transportation Technology Center, Inc. (TTCI) developed a series of higher performance wheel steels that will ideally extend wheel life and reduce premature wheel removal and wheel failure related derailments. This *Technology Digest* details the mechanical testing results of these steels (identified as SRI). The mechanical properties reported here are preliminary. Hardness, yield strength, and endurance limits are expected to be further improved on the actual wheels produced using these steels. One of the SRI rail steels (SRI-3) has been selected to cast a heat of wheels.

Laboratory test results for this steel have shown significantly higher mechanical properties when compared to current Class C wheel steel.

The following table summarizes the increases in mechanical properties for the SRI-3 steel in comparison to conventional Class C wheel steel:

Characteristic	**Improvements of SRI-3 Steel Over Class C**	
	Aluminum-killed	**Vacuum Treated**
Yield Strength	38%	28%
UTS	8%	1%
Elongation	22%	3%
Hardness	TBD	TBD
Fracture toughness	8.4%	-7.5%

The major advantages of SRI-3 steel is its higher fatigue resistance (including endurance limit), which is to some extent attributed to vacuum degassing and alloying.

Axle loads and traffic for the North American railroads have been continually increasing. However, the wheel steel has not been significantly modified to reflect this increase. Thus, with these increases in loading and traffic, the demand for better and more wear and fatigue resistance wheel steel is evident. Higher performance wheels will reduce the current premature removal of wheels and the number of wheel failure related derailments. In 2006, the associated cost for wheel removal and wheel failure related derailments was approximately $650 million. In order to reduce this high industry cost, TTCI is investigating the major causes of premature wheel removal and wheel failure and developing higher performance wheel steels with improved wear and fatigue properties that will increase wheel life.

INTRODUCTION

The increase in axle loads and traffic density for North American railroads requires continuous improvement of track and rolling stock components. Analyzing a 5-year trend from 2003 to 2007 reveals the average number of fatigue-related wheel failures at approximately 92,000 while the number of wear-related wheel removals were over 181,000. Fatigue-related failures represent a significant cost to the industry.

According to statistics of the Association of American Railroads (AAR), wheel cost is estimated at $68.6 million in 2007 for early removals due to fatigue-related failures.[1] In addition, derailments related to wheel failures were approximately $29.6 million in 2007.[2] Consequently, safety and wheel related cost was estimated to be over $98 million.

In order to minimize this cost and increase transit efficiency, TTCI established a research project under the AAR's Strategic Research Initiatives Program to reduce the number of heavy axle load wheel failures.

The main objective of the SRI project is to investigate the cause of premature wheel removal and wheel failure, which allows proposing potential remedies to increase wheel performance, thus a unique high performance steel (coded as SRI) for heavy haul wheel applications. TTCI has identified and invited domestic and foreign wheel manufacturers that have developed high performance wheels to participate in this project.

ADVANCED WHEEL STEEL DEVELOPMENT

AAR Class C wheel steel is commonly used for both general and heavy haul service. Table 1 lists the specified chemical composition of Class C wheels. Preliminary TTCI research results indicate that in order to improve the performance of Class C wheel steel, cleaner microstructures and higher mechanical properties are required.

Table 1. Chemical Composition of Class C Wheel Steel

Element Amount (wt%)	C	Mn	P	S	Si
	0.67-0.77	0.6-0.9	<0.03	0.005-0.04	0.15-1.0

Residual Elements							
Ni	Cr	Mo	V	Cu	Al	Ti	Nb
<0.25	<0.25	<0.1	<0.04	<0.35	<0.06	<0.03	<0.05

Microstructural defects (voids and nonmetallic inclusions) have negative effects on mechanical properties of materials, in particular when used under dynamic loading (e.g., heavy haul wheels). Consequently, cleaner wheel steels will have higher endurance limits that result in an increase in fatigue life, including reduced shelling of wheels, which will potentially prevent premature wheel removal. Previous attempts to demonstrate the effect of steel microcleanliness on fatigue performance for railway components have been published in railway industry publications.[3,4] Figure 1 shows an example of a typical casting defect (void) on the microstructure of a wheel removed prematurely from revenue service due to excessive shelling. The pore in Figure 1 is relatively large and was found away from the severe shelling location. The equations in Figure 1 are included to show the effects of the size and the shape 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 particular location. It is the parameter that quantifies the weakening of the steel or reduction in endurance limit due to the presence of microstructural defects (inclusions and voids). Unfortunately, the equations in Figure 1 do not take into account the effects of distribution or the nature of the defect, among other parameters that further contribute in the reduction of wheel life.

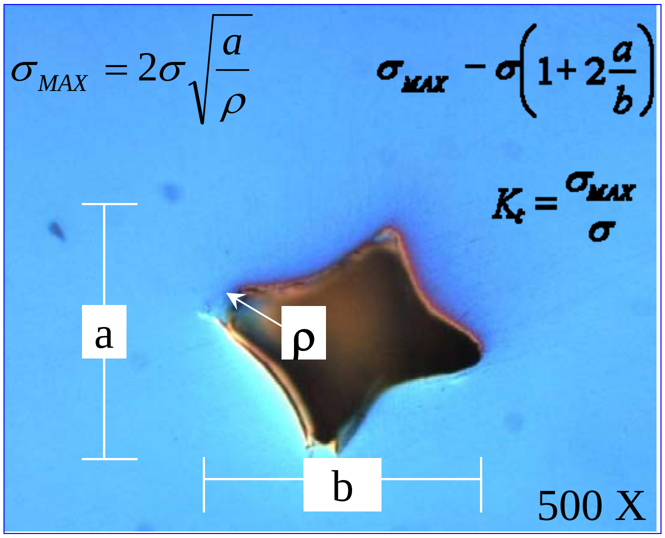


Figure 1. Effect of a pore on stress intensity; the equations show the effects of the shape and the size of the defect on the stress intensity factor (K_t).

TTCI expects that wheel life can be increased by using steels with higher mechanical properties. For instance, higher hardness has been demonstrated to be the simplest and most effective way to improve wear performance on rails,[5] although an excessive increase in hardness can also be detrimental. Excessive carbon can result in undesirable levels of pro-eutectoid cementite at the prior-austenitic grain boundary. Pro-eutectoid cementite has been associated with a reduction in the resistance to crack formation which in turn lowers fatigue life (e.g. rolling contact fatigue, thus shelling), elongation, and fracture toughness.[5] For this reason, the proper combination and amount of key alloying elements (e.g., Mo, V, Nb, Mn) are of great importance and can result in improvements in mechanical properties, as Figure 2 shows. However, alloying elements in excess (e.g., Mo) can cause a drop in mechanical properties and in extreme cases can compromise the integrity of the components.

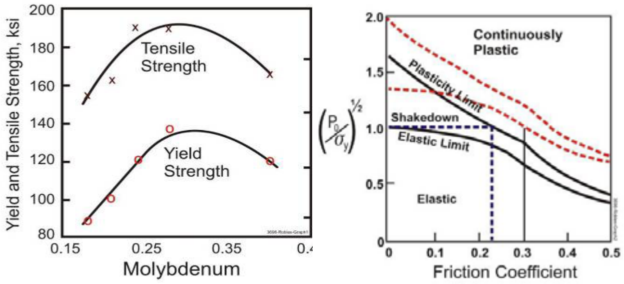


Figure 2. Effect of Molybdenum on Tensile Properties and Effect of Higher Yield Strength on Shakedown Limit[7]

ALLOY DEVELOPMENT

The above issues were used by TTCI as a basis to develop a series of high performance wheel steels (coded SRI) for demanding heavy axle load conditions in the North American railroads. The main objective of these steels is to mitigate, as much as possible, premature wheel removal and derailments associated with wheel failures.

TTCI has currently developed three SRI steels with unique compositions (currently under patenting process). As a first step, laboratory heats of three different SRI compositions of approximately 150 pounds were cast, heat treated, and rolled to simulate the wheel manufacturing processes. The as-heat treated and as-forged samples were used for mechanical testing purposes. In parallel, two ingots of the Class C wheel steel were cast; one using a conventional aluminum killed method and the other under vacuum treatment conditions.

The Class C wheel steel ingots were cast for comparison purposes and identification of improvements in mechanical properties for the SRI steels. The aluminum killed ingot was cast to demonstrate that vacuum degassing can increase mechanical properties, particularly fatigue-related properties. All experimental laboratory heats were tested for tensile strength, hardness, and fracture toughness using standard ASTM procedures. All samples were tested under similar conditions, which allowed a direct comparison to identify the potential advantages of the SRI steels.

The SRI steels were developed using low levels of sulfur and phosphorus and were vacuum treated to reduce the level of microstructural defects (voids and nonmetallic inclusions). This modification reflects superior microcleanliness in comparison to the AAR Class C wheel steels. The SRI steels have small amounts of key elements (Mo, V and Nb). This will make the steels more resistant to wear, fatigue, and shelling.[5,6] Figure 3 is a micrograph of the microstructure of the SRI-3 steel as obtained from the experimental ingots in the as-rolled and as-heat treated condition. All samples were heat treated prior to the mechanical testing by heating the ingots at 1500°F for 1 hour followed by rapidly cooling (quenching) to 900°F for 1 hour (tempering), then cooling to room temperature under normal heat exchange conditions. Wheel manufacturers commonly use the above described heat treatment on Class C wheels.

Figure 3 shows the presence of pearlite with traces of prior-eutectoid ferrite at the grain boundaries. The incentive for the use of this combination of phases in the microstructure is to have the well-known high wear resistance of pearlite together with the ferrite at the grain boundaries to prevent the presence of pro-eutectoid cementite.[7] This will reduce the propensity of crack initiation along the grain boundaries, thus reducing shelling. In addition, the thermal analysis results show that this steel is resistant to martensite formation, which can result in a lower tendency for spall formation.

Some of the tests were conducted on the steel in the as-cast condition as well as in the hot-rolled condition to determine the benefits for the SRI steels under different forging conditions. The results of the mechanical testing indicate that two of the SRI steels have comparable and in some cases superior mechanical properties to the Class C wheel steel (Table 1; also see Figures 4 and 5 on page 4).

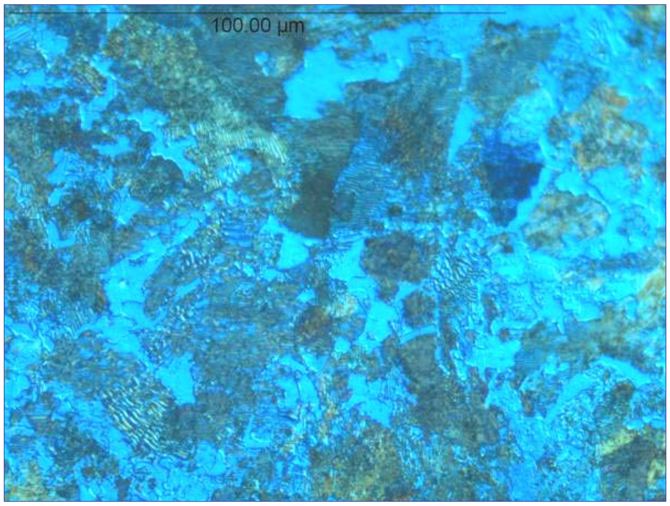


Figure 3. Pearlitic Microstructure of the SRI-3 Premium Wheel Steel showing Low Inclusion Levels

Table 2 gives the preliminary results of the tensile and hardness tests for the SRI and the regular Class C steels. It is important to mention that these mechanical properties have not been optimized, because the tests were conducted on experimental ingots, which were not heat treated under optimum conditions. Nonetheless, all steels were heat treated under the exact same conditions (typical Class C wheel steel heat treatment). It is important to notice the increase in mechanical properties of the Class C steel cast under vacuum degassing over the one cast using the aluminum killed condition. SRI-1 and SRI-2 steels have comparable mechanical properties and better elongation characteristics than Class C wheel steel. However, SRI-3 steel has noticeably better mechanical properties with slightly lower elongation characteristics as compared to the vacuum degassed Class C wheel steel, but its elongation is higher when compared to the aluminum killed Class C wheel steel.

Table 2. Preliminary Mechanical Test Results for the Experimental SRI Steels and the Class C Wheel Steel

Steel	Yield (ksi)	UTS (ksi)	Elongation (%)	Hardness (HB)
Class C‡	76.6	146.5	16.1	302
Class C	71.9	139.2	19.1	302
SRI-1	67.0	139.0	16.1	277
SRI-2	73.1	139.4	17.2	285
SRI-3†	98	149.8	19.7	302

‡Class C Vacuum Treated, †Best SRI (candidate) steel, the mechanical properties will vary for the actual wheels once the heat treatment is optimized.

Figure 4 shows the results of fracture toughness tests. In addition, the fatigue test results shown in Figure 5 further confirm that the SRI-3 steel is superior to Class C steel. Some of the advantages identified for the SRI-3 steel as compared to the Class C wheel steel are shown in Figures 4.

These results do not imply that cast wheels necessarily have lower mechanical properties as compared forged wheels. Cast wheel mechanical properties can be controlled by the manufacturer in terms of feedability, chemical composition, and cooling rates, which will produce acceptable properties.

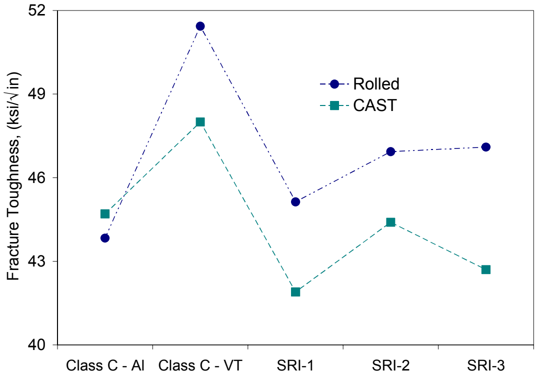
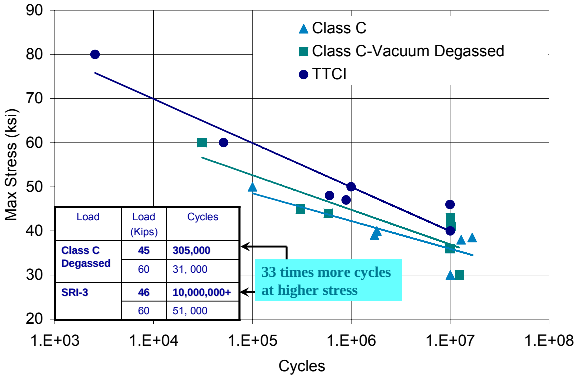


Figure 4. Results of Fracture Toughness for the As-Cast and As-Rolled Plate Samples (Al = Al-killed, VT = Vacuum Treated)



Load	Load (Kips)	Cycles
Class C Degassed	**45**	**305,000**
	60	31, 000
SRI-3	**46**	**10,000,000+**
	60	51, 000

33 times more cycles at higher stress

Figure 5. Fatigue Results of Class C and SRI-3 Steels

Figure 5 shows the results of fatigue performance for the SRI-3 steel and the Class C wheel steel cast under Al-killed and vacuum treated conditions. Figure 5 demonstrates the potential improvement in fatigue performance for Class C wheel steel cast under vacuum treatment conditions. Thus, the microstructural defects (porosity and nonmetallic inclusions) can reduce wheel performance. Therefore, it is expected that SRI-3 steel will render superior performance in service due to its higher mechanical properties; in particular, its improved fatigue properties. In addition, TTCI expects that SRI-3 steel will prevent shelling and potentially vertical split rims. As a result, the implementation of vacuum treatment in the manufacture of wheels for heavy haul use is strongly recommended.

Based on the results from the mechanical testing, the steel labeled as SRI-3 was selected as the candidate steel to cast a large heat of steel to produce experimental high-performance wheels. The experimental SRI-3 wheels will be forged and evaluated together with wheels from other manufacturers through mechanical, metallurgical, and full-scale tests.

CONCLUSIONS

TTCI expects that the final forging and optimal heat treatment will give the SRI-3 premium wheel superior mechanical properties, and these advantages will be demonstrated during the full-scale test.

The SRI steels show comparable or higher mechanical properties than Class C wheel steel. With the exception of a minor decrease in fracture toughness, the SRI-3 wheel steel has superior mechanical characteristics as compared to Class C wheel steel. Microcleanliness, alloying, forging, and vacuum treatment are the major factors that resulted in the increase in mechanical properties for the SRI-3 steel.

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