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## High Temperature Tensile Properties of High Performance Wheel Steels

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### Summary

High temperature tensile tests have been conducted on eight high performance wheel steels as part of the Association of American Railroads' (AAR) Strategic Research Initiatives (SRI) Program to prevent wheel failures. This SRI is developing and testing high performance wheels to improve the wear and fatigue performance in revenue service.

As expected, tensile tests conducted at four temperatures, between 70°F and 1,000°F, showed that all of the high performance wheel steels exhibited a substantial drop in yield strength at elevated temperatures. The three wheel steels with the highest room temperature yield strength (labeled 5, 6, and SRI) maintained this advantage over the other wheel steels regardless of temperature. These increased yield strength values should translate into improved resistance to rolling contact fatigue damage over the temperature range tested compared to AAR Class C wheel steel. The other high performance wheel steels included in the test had yield strength properties similar to those of AAR Class C wheel steel.

Griffin, Lucchini, OneSteel, Standard Steel, Sumitomo, and Valdunes donated high performance wheels for this project. OneSteel is participating with two steel formulations. The SRI wheel steel is also being tested as part of this program.



**INTRODUCTION**

As part of the AAR’s SRI program to prevent wheel failures, high temperature tensile testing has been conducted on eight types of high performance wheel steel. The goal of this project is to develop and demonstrate the benefits of high performance wheel steels, specifically focusing on improvements in resistance to wear and fatigue.

Griffin, Lucchini, OneSteel, Standard Steel, Sumitomo, and Valdunes donated high performance wheels for this project. OneSteel is participating with two steel formulations. Transportation Technology Center Inc.’s high performance wheel steel known as the SRI wheel, is also being tested. With the exception of the SRI wheel, a generic naming convention was used to identify each manufacturer’s wheels.

Seven of the eight high performance wheels have a pearlitic microstructure, which is similar to AAR Class C wheels currently used in North American freight service. One wheel, identified as wheel 6, had a bainitic microstructure.

**BACKGROUND**

Tensile testing at multiple temperatures was performed to assist in evaluating the resistance of the high performance wheel steels to damage from rolling contact fatigue (RCF) and thermal mechanical shelling (TMS). Shakedown theory can be used to estimate how repeated rolling contact will affect a material.<sup>1</sup> Stresses produced by rolling contact might produce purely elastic strains, subsurface plastic strain, or surface plastic strain. Plastic deformation leads to fatigue damage.

Figure 1 shows the shakedown diagram. The shakedown limit is the limit for continuous deformation under repeated loading. Calculations of this limit change, depending upon assumptions made regarding the contact conditions. The shakedown limits under full-slip conditions for pure lateral and pure longitudinal loading are plotted on the axes. The exact location of the shakedown limit line is a subject of some debate. In fact, it may be more accurate to identify it as a shakedown limit zone, rather than a line. The area below this zone represents conditions where only elastic deformation is likely to take place. The area above this zone represents conditions where plastic deformation is likely to take place. Regions where the plastic deformation occurs below the surface of the wheel or on the surface of the wheel are labeled. Contact conditions far beyond shakedown may result in wear instead of RCF damage.

In the shakedown diagram, the maximum normal stress in the contact patch ( $P_0$ ) is divided by the shear yield strength ( $K$ ) and plotted against the traction coefficient (ratio of tangential force to normal force). Traction coefficient values can range from zero to the wheel/rail coefficient of friction.

Determining the mechanical properties of wheel steel is essential to properly defining both  $P_0$  and  $K$ .  $K$  is directly proportional to yield strength.<sup>2</sup>

$$K = \text{Yield Strength} / \sqrt{3}$$

Hertzian contact theory allows  $P_0$  to be calculated as a function of the normal force between the wheel and rail, contact geometry, and the elastic modulus.<sup>3</sup> Lower values of elastic modulus allow for more elastic wheel deformation, thereby increasing the area of the contact patch and resulting in lower values of  $P_0$ .

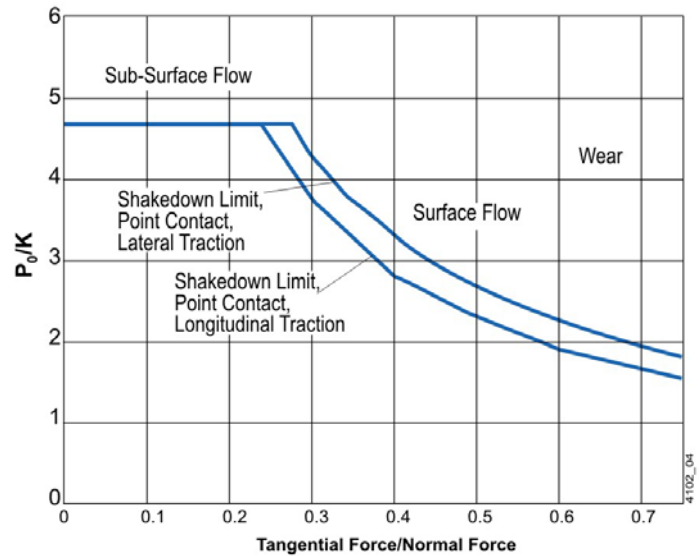


Figure 1. Shakedown Diagram

Elevated temperatures tend to result in a decrease of the yield strength and the elastic modulus in steel. In relation to the shakedown diagram, this produces competing effects by reducing the values of  $P_0$  and  $K$  simultaneously.

**PROCEDURE**

The relationship between temperature and tensile properties was quantified for the high performance wheel steels included in this project by conducting tensile tests at 70°F (room temperature), 600°F, 800°F, and 1,000°F.

The room temperature tests were conducted using 0.5-inch diameter specimens in a standard laboratory air environment according to America Society for Testing and Materials (ASTM) E8-08. The elevated temperature tests were conducted according to ASTM E21-05 in an inert argon gas environment to prevent oxidation. Test specimens were held at the test temperature for 30 minutes before the test started to ensure a constant temperature throughout the 0.35-inch diameter specimens. All specimens were harvested along the circumferential direction in the tread area of the wheels.

**TENSILE TEST RESULTS**

Table 1 shows the results of the tensile tests. As expected, all of the wheel steels exhibited a substantial drop in yield strength, ultimate strength, and elastic modulus at elevated temperatures.

Table 1. Tensile Test Results

Yield Strength (ksi)				
Wheel	70°F	600°F	800°F	1,000°F
1	115.3	99.3	83.8	55.6
2	100.6	83.4	69.6	42.5
3	105.7	96.2	72.3	51.9
4	116.7	102.8	80.4	49.1
5	144.7	121.5	105.0	76.1
6	161.8	129.8	121.9	87.7
7	113.9	95.2	83.0	47.1
SRI	146.4	119.1	106.7	73.2
AAR Class C <sup>4</sup>	113.5	Not reported	80.4	46.3
Ultimate Strength (ksi)				
1	158.5	157.9	118.2	77.1
2	159.8	145.9	104.5	61.4
3	159.1	150.2	107.9	70.8
4	177.6	163.5	118.3	72.1
5	190.5	173.2	140.5	97.6
6	179.4	160.7	142.1	105.1
7	174.6	156.6	120.4	69.8
SRI	193.5	173.6	140.3	95.4
AAR Class C <sup>4</sup>	164.5	Not reported	114.9	63.2
Percent Elongation				
1	3	8	13	25
2	15	32	32	35
3	13	25	31	25
4	13	27	29	33
5	12	20	15	27
6	13	16	16	24
7	14	27	27	30
SRI	14	22	24	31
AAR Class C <sup>4</sup>	10	Not reported	18	12
Elastic Modulus				
1	29.2	27.9	25.2	23.2
2	30.6	28.3	30.2	22.0
3	30.7	25.8	25.2	24.2
4	30.9	29.1	24.9	23.9
5	30.9	29.2	27.5	20.2
6	30.9	28.5	26.1	24.0
7	30.8	30.0	25.1	23.7
SRI	30.9	27.5	27.6	20.9
AAR Class C <sup>5</sup>	30.4	25.2 at 700°F		23.7

Figure 2 shows yield strength results. The bainitic wheel steel (wheel 6) had the highest yield strength at all temperatures tested. The three wheel steels with the highest room temperature yield strength (5, 6, and SRI) maintained this advantage over the other wheel steels, regardless of temperature. Wheels 1, 4, and 7 had yield strength values

similar to those of AAR Class C wheel steel at 70°F and 800°F. These three wheel steels showed higher yield strength at 1,000°F than AAR Class C steel. Wheel 3 yield strength was below that of AAR Class C steel at 70°F and 800°F, but above AAR Class C steel at 1,000°F. Wheel 2 yield strength was below that of AAR Class C wheel steel at all temperatures tested. In general, the elastic modulus values decreased as temperatures increased for all of the steels tested.

The ultimate strength and percent elongation values obtained during the tensile tests are listed in Table 1 for reference purposes. These properties do not figure prominently in resisting damage from RCF.

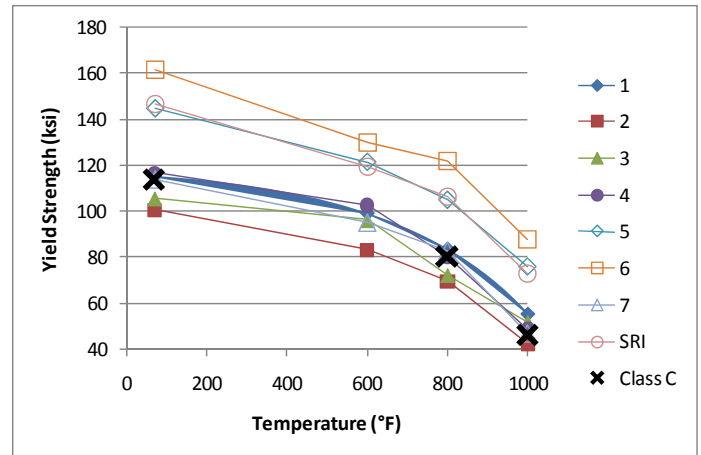


Figure 2. Yield Strength

**DISCUSSION**

Based on the tensile test results for yield strength and elastic modulus, P<sub>0</sub> and K values were calculated and applied to the shakedown diagram. Table 2 shows the values of P<sub>0</sub>/K and the associated shakedown limit in terms of traction coefficient for lateral traction. Figure 3 shows a selection of these values on a shakedown diagram.

P<sub>0</sub> values were calculated based on a wheel normal force of 35,750 pounds, wheel rolling radius of 18 inches, wheel transverse profile radius of 10,000 inches (representing a new wheel), and rail transverse profile radius of 14 inches. For the AAR Class C wheel steel, the elastic modulus value at 700°F was used to compute the P<sub>0</sub> value at 800°F, because an elastic modulus value at 800°F was not reported in the literature.

The shakedown diagram does not account for the beneficial residual stresses that are imparted to the wheels during the heat treatment operation by the manufacturer. These stresses can be relieved by holding the wheel at an elevated temperature for a period of time. For example, it is estimated that if the wheel was held at 800°F, 50 percent of the residual stresses would be relieved in 5 minutes and 100 percent would be relieved after 1 hour.<sup>6</sup> Lower temperatures would require much longer times to relieve residual stresses and higher temperatures would relieve residual stresses more quickly.

Table 2. Calculated P<sub>o</sub>/K and Shakedown Limit Values

Wheel	P <sub>o</sub> / K				Shakedown Limit (Lateral Traction Coefficient for RCF Damage)			
	70°F	600°F	800°F	1000°F	70°F	600°F	800°F	1000°F
1	2.9	3.2	3.6	5.1	0.46	0.41	0.37	0.00
2	3.4	3.9	4.9	6.5	0.39	0.33	0.00	0.00
3	3.2	3.2	4.2	5.6	0.41	0.42	0.31	0.00
4	3.0	3.2	3.7	5.9	0.45	0.41	0.35	0.00
5	2.4	2.7	3.0	3.4	0.57	0.49	0.44	0.39
6	2.1	2.5	2.5	3.3	0.64	0.54	0.53	0.40
7	3.0	3.5	3.6	6.1	0.44	0.37	0.36	0.00
SRI	2.4	2.7	3.0	3.6	0.57	0.50	0.45	0.36
AAR Class C	3.0	-	3.7	6.2	0.44	-	0.35	0.00

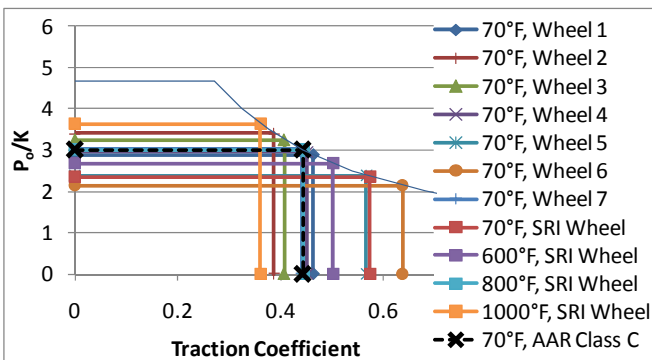


Figure 3. Shakedown Diagram for Various Wheel Steels

Because the shakedown diagram becomes less accurate at high temperatures due to changes in residual stress, the shakedown limits shown in Table 2 at 800°F and 1,000°F are shaded gray and should be used with extreme caution. Also, the lateral traction shakedown line used to calculate the shakedown limits listed in Table 2 is less conservative than the longitudinal traction shakedown line (see Figure 1), meaning that RCF damage may start to occur on wheels at traction coefficients slightly lower than the values shown. Despite these limitations in the analysis, the higher yield strength of some wheel steels (wheel 6 in particular, as well as wheel 5 and the SRI wheel) should provide improved resistance to RCF and TMS damage compared to AAR Class C wheels.

While not every wheel in revenue service will experience temperatures as high as 1,000°F, many wheels are exposed to elevated temperatures, particularly when negotiating descents of long grades. For example, data from a wayside wheel temperature detector was analyzed for 825 trains descending a 7-mile long, 1.4 percent grade.<sup>7</sup> Approximately 1 in every 24 cars had at least one wheel exceeding 500°F, 104 trains had at least one wheel exceeding 700°F, and 23 trains had at least one wheel exceeding 900°F. These were the temperatures of the wheel rim and plate as reported by the wayside wheel

temperature detector, but the temperature of the wheel tread surface was likely at least 100°F hotter (ie. 600°F, 800°F, and 1,000°F, respectively).<sup>8</sup>

**CONCLUSION**

Tensile tests conducted at four temperatures, between 70°F and 1,000°F, showed that all of the high performance wheel steels exhibited a substantial drop in yield strength at elevated temperatures, as expected. The three wheel steels with the highest room temperature yield strength (labeled 5, 6, and SRI) maintained this advantage over the other wheel steels regardless of temperature. According to shakedown theory, these increased yield strength values should translate into improved resistance to RCF damage over the temperature range tested. The other high performance wheel steels included in the test have yield strength properties similar to those of AAR Class C wheel steel.

Wheels manufactured from the steels discussed in this report are undergoing a durability test at the Transportation Technology Center. In August 2009, a revenue service test of the high performance wheels was initiated on a Union Pacific coal train.

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