U.S. Department of Transportation
Federal Railroad Administration

Office of Research,
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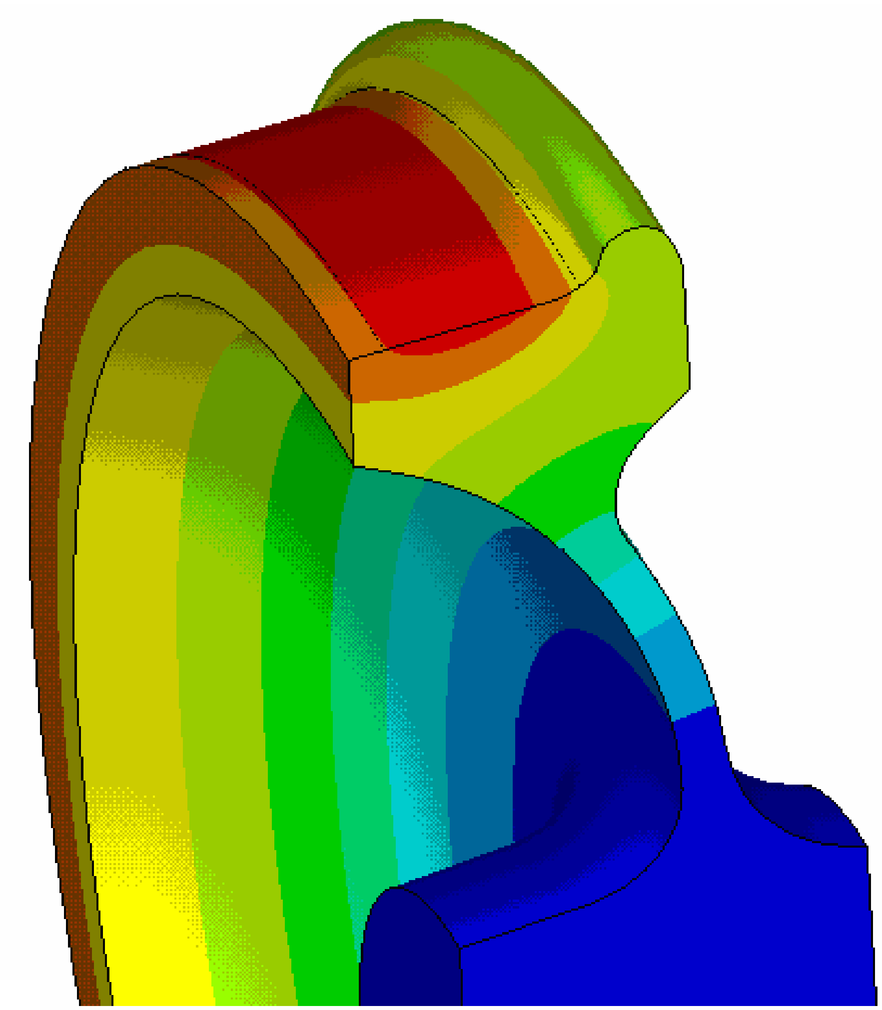
Washington, DC 20590

Effects of Temperature on Wheel Shelling



DOT/FRA/ORD-20/17

Final Report | May 2020

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 2020	Technical Report 2014 to 2015

4. TITLE AND SUBTITLE
Effects of Temperature on Wheel Shelling

5. FUNDING NUMBERS
DTFR53-11-D-00008
Task Order 343

6. AUTHOR(S)
Daniel Szablewski, Scott Cummings, Lucas Welander

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Transportation Technology Center, Inc.
55500 DOT Rd.
Pueblo, CO 81001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Railroad Administration
Office of Railroad Policy and Development
Office of Research, Development and Technology
Washington, DC 20590

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DOT/FRA/ORD-20/17

11. SUPPLEMENTARY NOTES
COR: John Punwani and Monique Ferguson Stewart

12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the FRA website.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
In 2014, Transportation Technology Center, Inc. (TTCI) reviewed and summarized published data and the capabilities of twin disk machines that included a unique machine that allows elevated temperature testing. TTCI suggested a methodology for future testing on this thermally controlled twin disk machine. Researchers reviewed existing literature regarding the relationship between temperature and wheel properties such as yield strength, residual stress, and shelling life. Comments are included on historical changes in wheel life, trends in removal causes, and important changes to the wheel operating environment such as the introduction of the AAR M-976 truck and changes to the AAR brake ratio requirements.

14. SUBJECT TERMS
Wheel shelling, twin disk machines, rolling stock, testing, methodology, yield strength

15. NUMBER OF PAGES
28

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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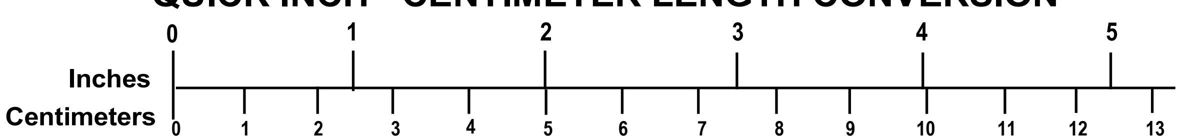

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

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Executive Summary

The Federal Railroad Administration contracted Transportation Technology Center, Inc. to develop a test methodology for the temperature-controlled twin disk test machine. The work occurred in 2014 and included a visit to a research facility in Japan to inspect a twin disk test machine uniquely equipped with temperature control. All other associated labor for the literature review, documentation of the proposed test methodology, and report preparation occurred in the United States.

Twin disk roller machines have been used for decades to study rolling contact fatigue (RCF) and consist of two rollers that are pressed together while the disks are rotated to simulate wheel/rail contact. One disk represents the wheel and the other disk represents the rail. Such machines can provide fast and cost-effective results due to the relatively small size of the disks and their continuous rolling action. Using twin disk roller machines, the effects of contact pressure, slip ratio, and lubrication on the development of RCF cracks have been quantified. Recently, the owner of a twin disk roller machine has added an induction heating coil to control the temperature of the “wheel” disk. This twin disk roller machine now provides the ideal test environment to quantify the relationship between wheel temperature and the number of load cycles until shelling appears. Understanding this relationship will allow future research to focus properly on the root causes of wheel shelling.

The test methodology developed during this project and described in this document allows for an initial test phase to be conducted at ambient temperature and with thermal cycling to 572 °F (300 °C), and 932 °F (500 °C). Optimal additional test temperatures can be selected using the results of the initial testing.

1. Introduction

Under the sponsorship by the Federal Railroad Administration (FRA), Transportation Technology Center, Inc. (TTCI) performed a literature review in 2014 on the effects of elevated temperature on wheel shelling defects to document the current understanding of this issue in the railroad community. This literature review is done to guide potential future twin disk testing at elevated temperatures. A description of a test machine with this capability and a suggested test methodology is included to address the gaps in the current knowledge of the wheel thermal mechanical shelling (TMS) problem.

1.1 Background

Impact loads of more than 90,000 pounds are the number one cause for wheelset removals in the North American freight railroad industry. The impact loads generated by the wheels can affect the roller bearings, rail, and other track components. The source of the impact loads has been studied extensively by many interested parties, and it is generally agreed that wheel shelling contributes heavily to the problem of impact loads. Shelling is a fatigue process in which cracks initiate at or near the tread surface of the wheel and propagate until pieces of the wheel tread surface break out.

The literature review serves as a basis for the development of a test program to study the contributing effect of different operating conditions on wheel rolling contact fatigue (RCF) and shell formation in the twin disk setup. This literature review serves the purpose of reviewing and summarizing the published data and capabilities of twin disk machines. Emphasis is on analysis of critical issues that need to be considered when evaluating data from less-than-full-scale RCF test machines. Another area of focus is on reviewing the relationship between temperature and wheel mechanical properties and operating conditions and their effect on shelling resistance. In addition, this report addresses historical changes in wheel life, trends in removal causes, and important changes to the wheel operating environment including introduction of the Association of American Railroads' (AAR) M-976 truck and changes to the AAR brake requirements.

Material strength and residual stress are both thought to be important factors in a wheel's ability to resist damage from RCF. Both properties can be affected by changes in temperature. An attempt has been made in the literature to establish a wheel temperature below which the shelling resistance of a wheel is not negatively affected. However, the analysis did not include any supporting test data. Unfortunately, no publicly available evidence has been presented that can confidently quantify the relationship between wheel temperature and wheel shelling.

1.2 Objectives

The objectives of this work were to provide a background about the state of knowledge regarding wheel performance at elevated temperatures, identify a means of improving this knowledge, and describe a productive way to generate necessary data.

1.3 Overall Approach

The background was provided via a literature review subdivided into several components consisting of an investigation of the current status of twin disk testing, RCF and wear mechanisms, and a summary of the operating environment of freight car wheels in North America. A twin disk testing machine capable of controlling the temperature of the wheel specimens during testing was identified as a means for improving the state of knowledge regarding wheel performance at an elevated temperature. A visit to this testing machine provided researchers with the opportunity to view the machine and discuss its operating characteristics with the owners of the machine. Based on this improved understanding of this test machine, a methodology was proposed for future testing.

1.4 Scope

The scope of work for this project includes a literature review, a visit to a unique twin disk test machine with temperature control at a facility if Japan, and the development of a test methodology to utilize this twin disk test machine to provide data which is lacking in the available literature. Actual testing of specimens on the twin disk machine is outside the scope of work for this phase of the project.

1.5 Organization of the Report

This report provides introductory and background information in Section 1. Section 2 analyzes and discusses the literature review, while Section 3 offers an overview of unique twin disk testing machine with temperature control and a proposed test methodology to utilize this test machine. Section 4 summarizes the work performed.

2. Literature Review

2.1 RCF Damage Mechanism

RCF damage mechanism in rolling wheels is manifested as spalls or pits formed by fatigue cracking under cyclic load conditions until the material cracks and there is subsequent spalling. Another survey addressing RCF mechanism including crack initiation and propagation, monitoring technologies, and management of RCF in track was described in a comprehensive way [1]. However, wheels are subjected to increased temperatures from tread braking, and the effect of this temperature increase on the development of shelling is not well quantified.

2.2 Twin Disk Testing

Twin disk testing design was used in many studies to investigate disk properties and/or rolling surface conditions [2–10]. In one study, Ikoubel (2011) used twin disk testing as a method of RCF assessment on camring steel wheels. The work involved simulating, identifying, and evaluating RCF in short time for two different temper camring steels. Test conditions involved shape, running surface roughness, and friction coefficient evaluation on twin disk surfaces. Results showed that twin disk tests are useful in evaluation of pitting detection in RCF under lubricated conditions, and that the steel quality was of extreme importance to keep constant conditions in different test runs and to avoid data scatter [5].

Disk surfaces were evaluated using scanning electron microscopy tools. The indication was that high contact pressure induced adhesive damage in the samples. It was determined that this might accelerate RCF damage [5].

RCF damage could be retarded however through surface hardening methods, particularly induction heating. This method is used to selectively harden areas of a part or assembly without affecting the properties of the entire part (i.e., this is a surface treatment method). The steel is heated through noncontact elements that are themselves heated electromagnetically. They then transfer that heat to the surface of the steel component. Once the target surface temperature is reached, the part is then quenched. This forces the heated surface into a martensitic transformation, thereby making the surface harder than bulk metal structure. It also subjects the surface to high compressive residual stresses, which retards the onset of RCF crack initiation in service. This method has proven to extend the component fatigue life and wear resistance, as it also affects the residual stress of the treated surface [11] (see Figure 1). The effectiveness, however, depends on hardening depth and the magnitude and distribution of residual compressive stress in the treated surface layer [12]. Attention must be given to the selection of surface treatment temperatures and part geometries, as high temperatures might alter the treated parts' final dimensions, resulting in distortion if the treatment temperature is too high [12].

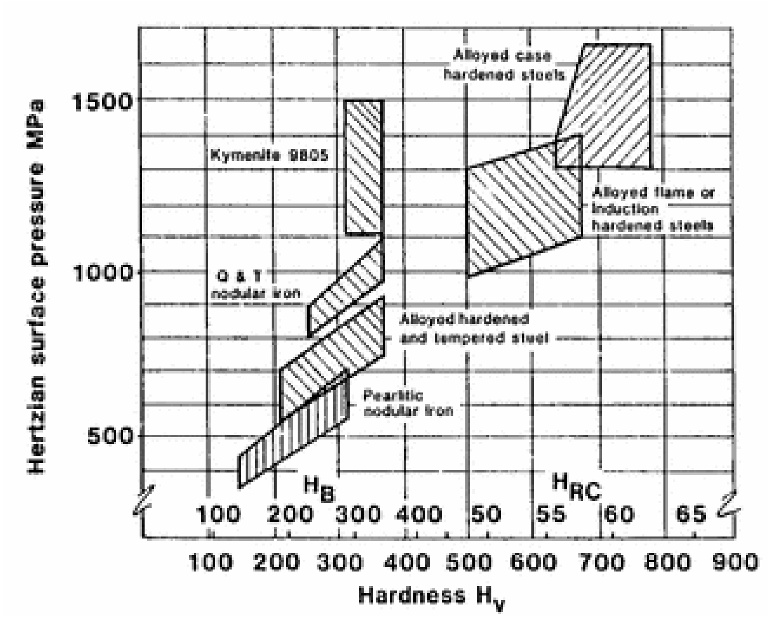


Figure 1. Fatigue limit of different materials due to Hertzian contact stress shown as a function of material hardness [11]

Another fatigue life consideration in rolling components is component surface roughness, which is of interest when trying to represent rolling contact on a test rig with components that are less than full scale. The normal force used in a twin disk machine can be adjusted to account for the smaller contact patch size of a scaled rig though Hertzian contact stress analysis. Although this allows for equivalent contact stresses to be generated, some authors caution that the surface roughness of the disks must be carefully considered, because asperities will have a larger stress contribution on a small-scale test compared to a full-scale wheel and rail test [13]. A finer surface tends to increase the RCF resistance. Roller-to-roller tests show that the shot peening surface treatment method increases RCF strength [14]. However, other studies indicate that shot peening increases part failure life only at contact pressure below 3 GPa [11]. One study concluded that surface finish between of 0.5 µm and 1.5 µm did not have a significant effect, but that surface finish better than 0.5 µm resulted in increased friction and reduced RCF life [8]. In other fatigue life studies of case-hardened steels, it was shown that optimum component life is obtained when surface carbon content is in the 0.6–0.8 wt.%C range, and the surface hardness is at least 700 HV [15].

Dwyer-Joyce et al. (2013) performed a study on twin disks that have been either artificially damaged with dents and scratches or run with particles of sand or ballast material. The disks were then loaded and rotated at realistic conditions of contact pressure and controlled slip. It was found that for normal operation of the contact, either dry or with water lubrication, surface dents and scratches have little effect on fatigue life, and the normal plastic flow in the roller surface acts to close the dents. The final failure mechanism was in the entire roller surface with no preference to dent location. On the other hand, if oil was used as the lubricant during roller operation, then plastic deformation was greatly reduced and the dents acted as stress raisers. Fatigue cracks were observed to originate on these dents. It was also found that sand particles that enter the contact patch increase the level of traction between the rollers while simultaneously increasing the level of plastic flow. In addition, high concentration of sand at the contact patch was observed to promote a low cycle fatigue process that caused very high wear and spalling on the running surface. From these studies, it was concluded that the presence of solid contaminants greatly accelerates the wear and low cycle fatigue in the immediate subsurface of the contact patch [16]. Kapoor (1994) defined the crack damage mechanism present in severe tribological conditions as "ratcheting" or "head check" (i.e., in the case of rail running surface), where each passage of the wheel causes an increment of plastic shear strain below the contact zone. In ratcheting, crack initiation was determined as the point at which ductility of the material is exceeded and rupture occurs [18].

The creepage on many twin disk test machines is controlled by varying the rotational rates to provide a longitudinal creepage. However, there are twin disk machines that produce lateral creepage through adjusting the angle of attack between the disks [10, 13].

2.3 RCF in Railway Wheels

Molyneux-Berry et al. (2014) described how the railway wheels RCF damage is influenced by the properties of the wheel material, particularly, steel composition and the wheel manufacturing process, as well as thermal and mechanical loading during operation. Their study investigated the influence of the as-manufactured steel microstructures and hardness, as well as the influence of wheel/rail contact conditions on the RCF damage and plastic metal flow on the tread of railway wheels. Steel mechanical properties in the wheel were observed to vary with depth from the tread surface and hardness changes. It was observed that in the 1–7 mm range below the wheel tread surface, the wheel/rail contacts during operation cause stresses that exceed the material yield stress, which leads to work hardening of that layer, without a microscopic change in the microstructure. This change in the subsurface material structure was determined to increase the likelihood of crack initiation on wheels toward the end of their life cycle [19].

Others described how the wheel manufacturing process is carried out [20–22], which can be divided into three parts: the first part, austenitization, is heating the wheel to 900 °C (1,652 °F), the second part is quenching of the rim to 300 °C (572 °F), and the third step is letting the wheel slowly air cool. This three-step process forces the rim of the wheel to become harder and sets up a residual compressive stress in the wheel rim. It has a twofold benefit of reducing wheel and rail wear, as well as preventing onset of RCF on the wheel running surface. It also makes the web, plate, and hub of the wheel relatively softer and thereby less prone to crack propagation. Following air cooling, the wheel is air tempered at 500 °C (932 °F), which achieves wheel surface properties that are resistant to surface damage.

It is important to note how RCF cracks in the wheel propagate, depending on wheel position relative to the track. Left- and right-hand curves set up two bands of cracks on the wheel. However, while one of these bands allows relatively rapid propagation of RCF, RCF in the other band propagates very slowly. The cracks near the flange of the wheel tend to be forced closed before contacting the rail and do not tend to propagate deep into the wheel. On the other hand, the cracks near the field side of the wheel are forced open before they contact the rail. Fluid entrapment and pressurization in the contact zone can propagate these cracks in the wheel material [19], see Figure 2. The change in material properties through the depth of the wheel rim would tend to increase the likelihood of RCF crack initiation on wheels toward the end of their life.

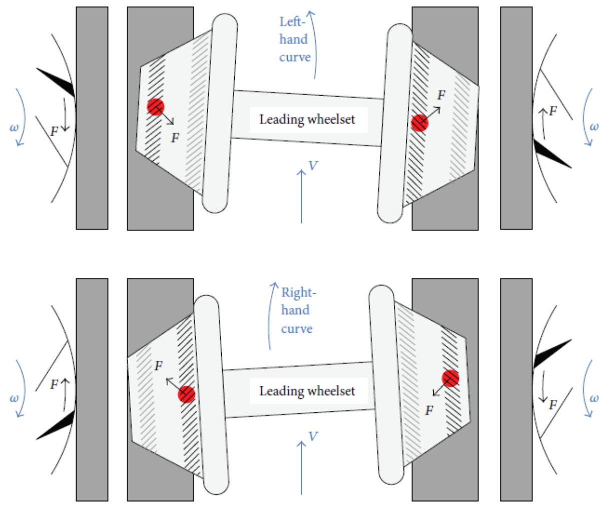
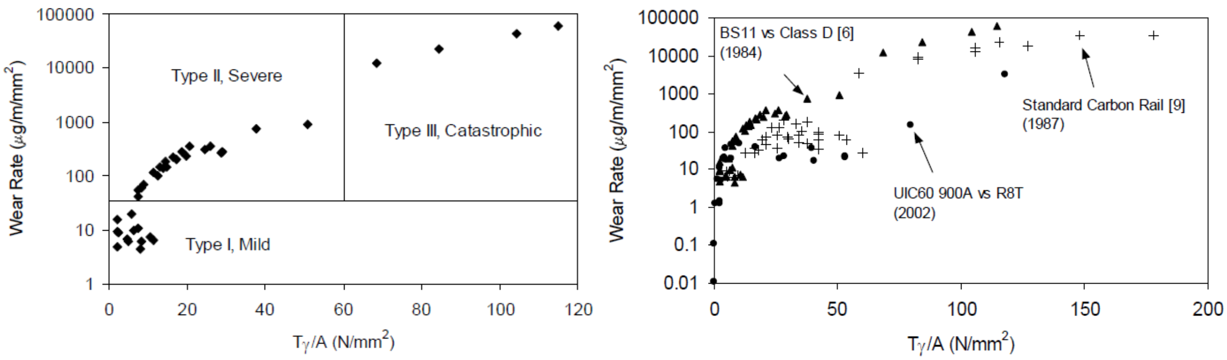


Figure 2. Left- and right-hand curves indicating bands of relatively rapid RCF growth and slower RCF growth [19]

Others produced maps of rail wear regimes taken from twin disk and pin-on-disk testing and attempted to relate these wear rates to the full-size wheel wear [23, 24]. Wear regimes and transitions were identified using the wear maps and defined in terms of slip and contact pressure. Wheels in general are subjected to both stick no slip and slip regions in the contact area. With increasing tangential load, the slip region increases and the stick region decreases, resulting in rolling and sliding contact. However, when the tangential load reaches saturation value, the stick region disappears and the entire contact patch enters a state of pure sliding. This is especially true in curved track [23]. The authors observed that during the sliding, an increase in the severity of loading leads at some stage to a sudden change in the wear rate (i.e., material volume loss per sliding distance). This wear can be subdivided into two basic regions: mild wear and severe wear [23]. Mild wear is characterized by a smooth surface, with minimal plastic deformation and free of oxide debris. Severe wear results in a rough surface with extensive plastic deformation and metallic flakes [25–27]. Plotting wear maps of wear rate against contact pressure and sliding velocity, the various territories associated with different wear mechanisms and the transitions from mild to severe wear can be identified [28]. Bolton et al. (1984) identified a third wear region they termed "catastrophic wear," where wear rates accelerate rapidly and surface quality of the wheel samples becomes very rough.

2.4 Twin Disk Wear Mechanism and RCF Crack Propagation

The approach of displaying the three mentioned wear regions (i.e., Type I: mild, Type II: severe, and Type III: catastrophic) graphically involves plotting wear rate in ($\mu g/m/mm^2$) (mass loss in micrograms per meter rolled per contact area in mm^2) against a ratio of tractive force (T) multiplied by slip (γ) (percentage difference in surface speed between the two disk wheels), and then divide that by the area of the contact patch (A): ($T\gamma/A$). Wear maps, such as the one in Figure 3 can then be created.



(a) (b)

Figure 3. (a) Wear maps of twin disk sample wear indicating the three wear regimes acquired from the lab testing of BS11 rail material and Class D tyre material, and (b) twin disk sample wear indicating testing of several different material combinations. The three types of wear regions can be identified in both cases [23]

The Type I mild wear regime is dominated by surface oxidation, whereas Types II and III wear regimes are dominated by sample running surface cracking and material loss by spalling [29]. As Figure 3 shows, there is a distinct transition between each regime with a distinct change in wear at each stage. Both mild and severe wear regimes have been identified on track during field tests [27].

Lewis and Olofsson (2004) explain that although the three wear regions can be identified by studying the operating test parameters in twin disk testing and measuring the wear rates as well as observing the disk surface quality, the mechanisms governing these wear type changes are not well understood. Some elaborate that disk surface temperature may play a role in the wear transitions [30]. In work done on R8T wheels, a quantitative analysis has been performed to relate the wear transitions between severe and catastrophic wear to the temperature in the contact patch between disks [24]. Temperatures calculated at the twin disk contact location were seen around the value at which a reduction in material yield strength occurs. Results shown in Figure 4 indicated that the transition from severe to catastrophic wear occurs between 200 °C (392 °F) and 300 °C (572 °F). These temperatures correspond with those causing a reduction in yield strength of carbon manganese steels similar to rail steels [31]. The authors of twin disk and pin-on-disk tests have verified the temperature calculations at the contact patch, and claim that the large increase in wear rate seen at the Type II and Type III transitions may indeed be due to thermally induced reduction in yield strength of the material and other material properties [23].

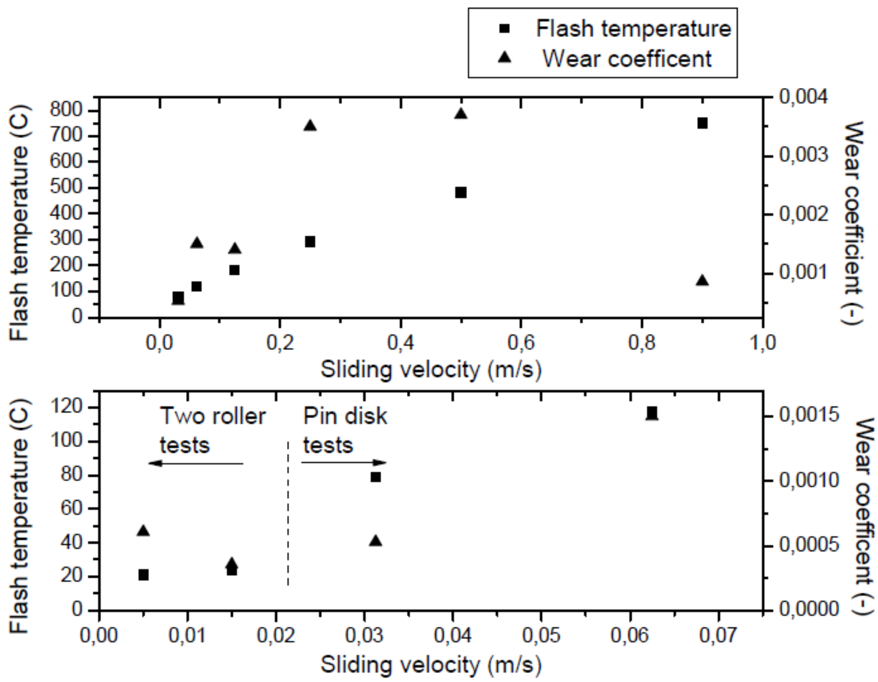
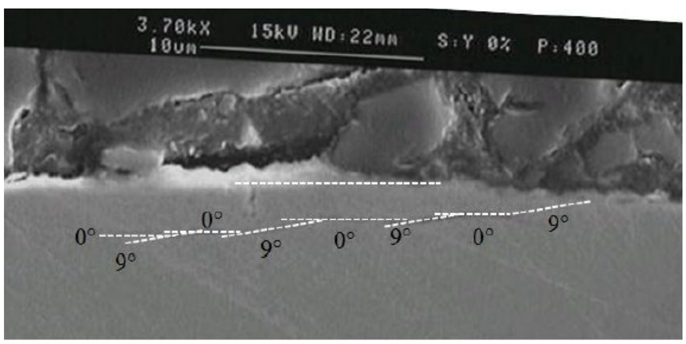


Figure 4. Contact temperatures and wear coefficients for twin disk tests and pin-on-disk tests for UIC60 900A rail material versus R7 wheel material (lower graph is a magnification of upper graph) [24]

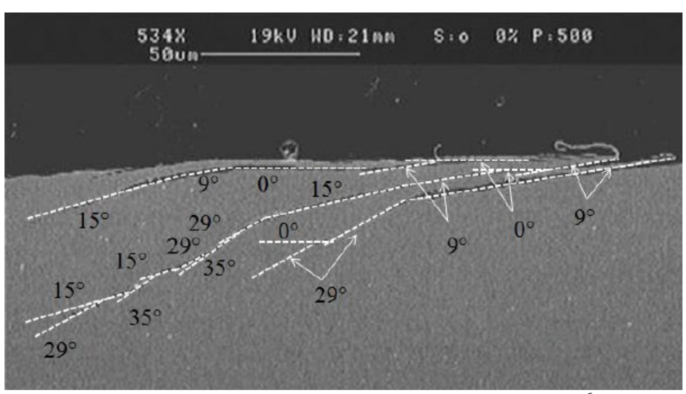
In another study, Roberti et al. (2012) undertook an investigation on the RCF crack path properties in R7T railway wheels steels. The effect of different test parameters on the RCF fatigue strength of the railway wheel steel was evaluated. Tests were conducted in both dry and water lubricated conditions with varying slip ratio, as well as a different P_o/k ratio (where 'P_o' is the maximum Hertzian pressure, and 'k' is the yield stress in shear of the material). An investigation included careful examination of crack initiation and growth directions. Observations were made that all cracks initiated at the surface. Even in the presence of subsurface nonmetallic inclusions, the initiation was still on the surface of the rolling wheel. The cracks subsequently propagated at shallow angles down into the microstructure of the wheel and at some point, branched, where one crack path propagated back toward the surface of the wheel and the other path propagated deeper into the wheel [32].

Fatigue crack life can be divided into two identifiable stages: stage I is shear stress driven initiation at the surface, followed by transient crack growth behavior; stage II is subsurface tensile and/or shear driven crack growth [33]. Roberti et al. (2012) determined in their study that stage I surface initiated RCF cracks are the consequence of shear band cracking controlled by ratcheting. Due to the hydrostatic pressure, the wheel material can withstand higher strain without failure compared to the uniaxial or biaxial loading conditions. These RCF cracks are usually reported to occur due to unidirectional plastic material flow caused by wheel versus rail sliding (creep) and high tangential forces. Crack angles in stage I are shallow to the wheel tread surface. Once a critical crack length is reached, the growth becomes governed by the stress and strain field near the crack tip [34]. The stage II crack propagation has been found to follow specific crack plane orientations present in the plastically deformed layer in the subsurface of the wheel contact. At the critical lengths, cracks can either branch upward, causing flaking of the wheel material, referred to as shelling or spalling, or grow further downward, with great danger to the wheel integrity.

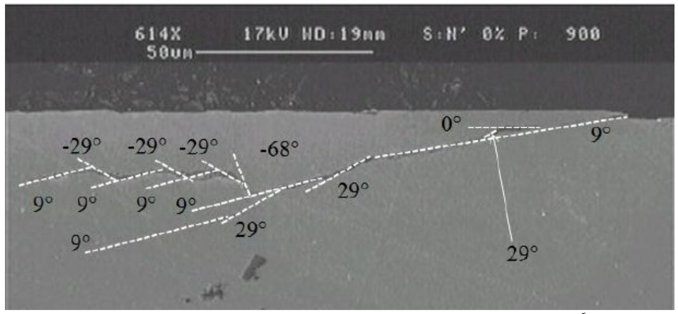
The Roberti et al. (2012) study performed twin disk Amsler machine tests with specimens machined out of a R7T steel wheel and 900A steel rail. Chemical compositions of both disks were of hypoeutectoid composition with similar chemistry ranges. During testing, the Hertzian contact pressure and creepage were varied, as were the dry and lubricated conditions on the running surface. In each case, the final cycle count was measured. Following testing, the samples were cut at mid-thickness to examine the RCF crack paths. It was found that dry contact with 0 percent creepage gave longer RCF lives at all Hertzian contact pressures analyzed. Also, the cracks at 0 percent creep tended to be shallow (i.e., had relatively small angles relative to the running surface). However, as soon as creepage percentage was introduced, even below 1 percent creep, the RCF initiation time was greatly reduced. Introducing higher creep values also allowed faster growth of RCF cracks (i.e., it took fewer cycles to get to the same growth as “no creep” condition), and in addition, the RCF cracks grew deeper into the material with higher angles relative to the running surface. If any branching was observed, it was usually deeper in the material, and branched cracks did not grow toward the surface, but progressed into the material as well. Higher contact stresses allowed for faster growth of cracks. Evidence of this is presented in Figure 5, where operating conditions and final cycle counts are noted adjacent to the observed final crack path [32]. Nonmetallic inclusions seen in Figure 5c and Figure 5e did not have a contributory effect on crack initiation, propagation, and/or branching.



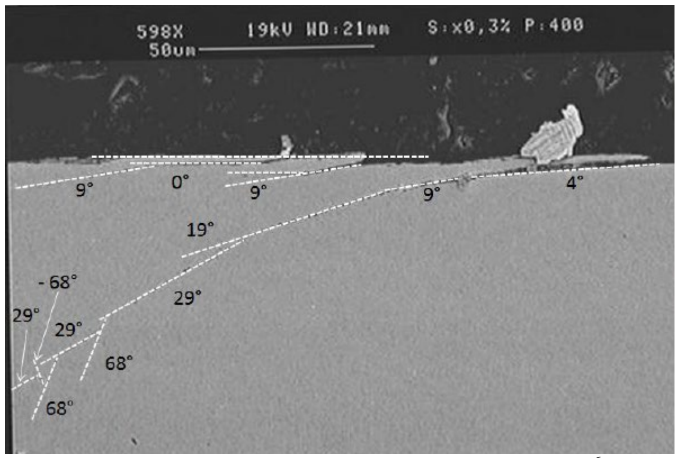
(a) Wet contact, 400 MPa, 0% creep, $2.3(10)^6$ cycles



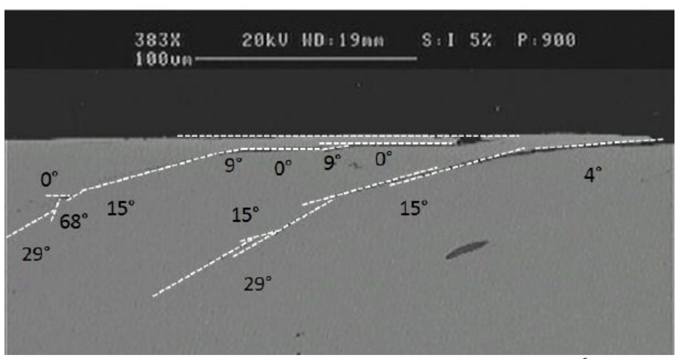
(b) Wet contact, 500 MPa, 0% creep, $1.1(10)^6$ cycles



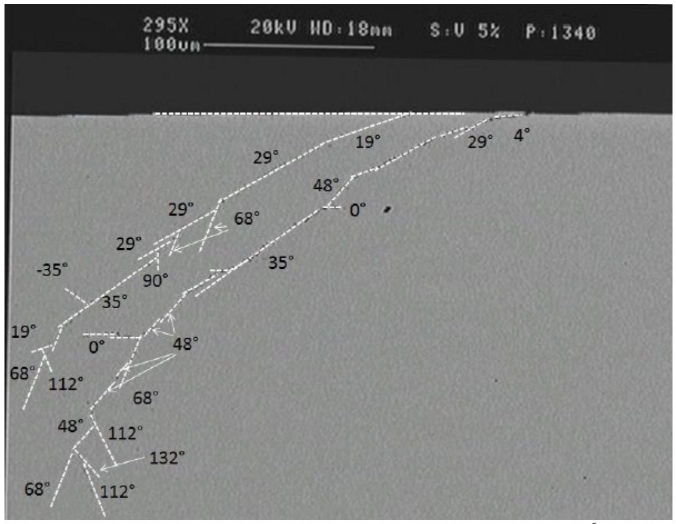
(c) Dry contact, 900 MPa, 0% creep, $2.6(10)^6$ cycles



(d) Wet contact, 400 MPa, 0.3% creep, $0.2(10)^6$ cycles



(e) Wet contact, 900 MPa, 5% creep, $0.3(10)^6$ cycles



(f) Wet contact, 1,300 MPa, 5% creep, $0.2(10)^6$ cycles

Figure 5(a–f). Twin disk RCF crack path in R7T steel wheel tests presented with crack angles calculated relative to the running surface. Lubrication conditions, contact stresses, creep, and final cycle counts are presented adjacent to each figure [32]

Very similar crack angles have been reported in another study [35], see Figure 6. Considering the observations of crack paths for different operating conditions, the general view is that crack initiation and subsequent transient growth roughly follows the plastically deformed material. While the deformed material is along a continuously curved path, the crack growth follows subsequent straight paths along differently oriented planes, with abrupt changes in crack direction. Very similar crack angles are observed independently of the condition of contact, either dry or wet. As a result, the effect of hydrostatic fluid pressurization due to fluid filling the cracks does not affect the crack plane orientation angles.

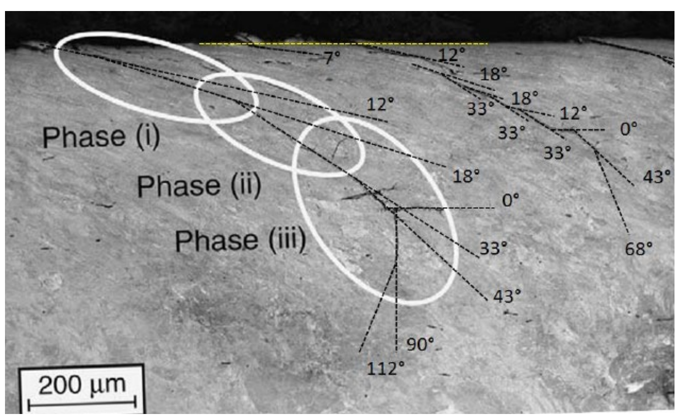


Figure 6. RCF crack path with defined plane orientations [35]

A theory for crack branching has been proposed by Makino et al. (2001). In this study, finite element modeling has shown that two peaks of $K_{\theta,max}$ occur during one cycle of rolling contact, and they cause branching in two directions: one crack branch toward the surface, and the other branch deeper into the material. For example, for an initiation crack angle of 25 degrees, finite element analysis calculated branching at 90 and -45 degrees, so at 65 and 70 degrees from the original crack path [36].

2.5 Operating Environment of North American Freight Car Wheels

North American freight car wheels are expected to safely carry heavy loads—typically a nominal level of 35,750 pounds per wheel—for several hundred thousand miles between reprofilings. The industry is continually in search of methods to improve wheel reliability and service life. Between 1995 and 2010, the rate of wheelset replacements per gross ton mile decreased approximately by 10 percent [37]. This change is notable as it occurred over a period in which average axle loads have increased, and new rules have been introduced to reduce the number of high-impact wheels—both of which might be expected to shorten wheel life. In addition, car brake ratio requirements were increased in 1999 and again in 2003. The increase in wheel life is potentially attributable to multiple factors including the widespread use of suspensions with improved steering, increased control of wheel/rail friction, improved rail grinding to maintain appropriate rail profiles, and improved steel quality.

In one TTCI study, life comparisons of revenue service full-size wheels were made for two car types in two different train sets, one fitted with 3-piece trucks and the other with AAR M-976 trucks [38]. The AAR M-976 truck, designed to improve steering, was first introduced into revenue service on a large scale in 2004. Studies conducted in revenue service showed that wheel removals could be reduced by introducing improved steering trucks [39]. In their study, TTCI observed an 18 percent improvement in wheel set miles to removal after 380,000 car service miles using the M-976 trucks [38]. By 590,000 car service miles, this improvement was observed to increase to 24 percent over the standard 3-piece truck [40]. This performance improvement was attributed to the steering improvements of the M-976 trucks. However, asymmetric wheel wear was observed in M-976 trucks leading to premature Why Made Code 60 (thin flange) wheel removals in high mileage coal car operation that was 6.6-fold increased over standard 3-piece trucks. The magnitude of the improvement in tread damage wheel removal observed suggests the dominance of steering tractions in determining wheel performance in North American western coal operation. This study also suggests that stuck brakes resulting in overheated wheels and slid flats might not be a major factor in wheel life for the cars analyzed. Ongoing TTCI studies are attempting to address the asymmetric wheel wear issues associated with M-976 trucks.

In another TTCI study, the effect of 3-piece trucks on wheel shelling was investigated. Wheel RCF was linked to one type of shell initiation [41]. Since wheel damage is the primary reason for wheel removal in North America, with TMS as a subset of wheel shelling, and RCF accounting for approximately half of the total wheel tread damage problems, the study focused on understanding the specific conditions in which RCF occurs and leads to shelling [42, 43]. Revenue service data was collected on the 3-piece trucks and shakedown theory, which was used to assess the predicted wheel RCF. The study concluded that the curve unbalance condition (i.e., a combination of track curvature, superelevation, and train speed) is an important factor in RCF initiation. Nearly all significant shakedown exceedances were recorded on curves of at least 4 degrees. In addition, wheel/rail coefficient of friction in curves can be a factor in RCF initiation and propagation. A direct comparison between two similar curves with new rail showed that the curve with some visible residual lubricant had less RCF than the curve that was very dry. On the other hand, rail profile and track conditions were not found to be a major factor in this analysis. The rail profiles at all inspected sites produced conformal contact with the instrumented wheelset wheel profiles. Observed rail RCF condition correlated well with shakedown theory prediction when considering rail age and curve unbalance conditions. The study also concluded that the use of M-976 trucks should reduce RCF over the use of standard 3-piece trucks.

In a NUCARS®* parametric simulation of dynamic wheel performance effect on RCF, TTCI conducted over 1,000 simulations of a loaded 1,272 kN (286,000-pound) hopper car studying the effects of multitude of parameters including wheel/rail profiles, lubrication, truck type, curvature, speed, and track geometry [44]. It was found that the degree of curvature is the single most important factor in determining the amount of RCF damage to wheels. In addition, this study found that M-976 trucks produce better wheel RCF life on typical routes than do standard 3-piece trucks. In most curves, the low-rail wheel of the leading wheelset in each truck was found to be the most prone to RCF damage. In addition, use of wheel flange lubricators and top-of-rail friction modification was found to have more benefit in wheel RCF prevention for standard 3-piece trucks than M-976 trucks. Avoiding superelevation excess (i.e., operating slower than curve speed) was found to provide benefits for wheels in cars with 3-piece trucks.

When investigating the wheel service temperatures and car conditions in relation to TMS, one study collected the wayside wheel temperatures through a wheel temperature detector (WTD) located near the bottom of a grade to explore the effect of wheel overheating on shell formation [45]. The data showed that most hot wheels, reading 500 °F and above, were found in trains descending from grade. A WTD typically reports a temperature that is 100 °F to 150 °F cooler than the tread temperature of the wheel during braking. Of the 825 descending trains analyzed, the WTD reported 393 trains that had at least 1 wheel greater than or equal to 500 °F and 104 trains with at least 1 wheel greater than or equal to 700 °F. As a continuation of this analysis, another TTCI study attempted to define a temperature range in which the life of an AAR Class C wheel is not shortened by premature fatigue and shelling [46]. It was found that residual compressive circumferential stresses play a key role in protecting a wheel tread from fatigue damage. As a result, temperatures sufficient to relieve residual stresses are a potential problem from a wheel fatigue point of view. It was determined that only the most rigorous train braking scenarios can produce expected train average wheel temperatures that would yield concern for reduced fatigue life. However, variations in wheel temperatures within individual cars are high enough to cause a reduction in wheel fatigue life. The maximum acceptable operating tread temperature for AAR Class C wheels was determined to be approximately 600 °F. The temperatures below the level required to relive residual stresses were found to not be harmful to AAR Class C wheels, and approximately 10 hours would be required to relieve any residual stresses in AAR Class C wheels at 600 °C.

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*NUCARS® is a registered trademark of Transportation Technology Center, Inc.

3. Controlled Temperature Testing

3.1 Test Facility

TTCI personnel visited Japan in April 2014 to meet with representatives from Nippon Steel & Sumitomo Metal Corporation (NSSMC) that owns the research facility containing a twin disk test machine with temperature control and Nippon Steel & Sumikin Technology (NSST) who performs the testing on this machine. The capabilities of the testing facility range from basic, off-the-shelf testing equipment to one-of-a-kind, state of the art instruments and machines. Figure 7 shows an aerial view of the research headquarters as no photography was allowed inside the facility.

Figure 7. NSSMC research headquarters in Amagasaki, Japan

The focus of the meeting was an information exchange regarding NSSMC's thermally controlled twin disk machine. This testing machine is unique due to the temperature control of the disk representing the wheel. Temperatures can be controlled to within ± 9 °F (± °C) over the range of ambient to 932 °F (500 °C). The design of the twin disk machine is proprietary and specific details of operation and monitoring are confidential to NSSMC. Some details regarding the test machine include:

- Maximum speed of 1,000 revolutions per minute (RPM)
- Controlled temperature of the “wheel” disk within the range of ambient to 932 °F (500 °C)
- Vibration monitoring
  - A test is stopped when the vibration due to surface condition exceeds 5 g’s
- Diameter of disk representing wheel is 4.72 inch (120 mm)
- Diameter of disk representing rail is 7.87 inch (200 mm)
- Loading range of 1,124 to 11,240 pounds (5,000 to 50,000 N)
- Typical high-pressure testing conducted with Hertzian contact pressure of 260 ksi (1,800 MPa)
- Contact patch width range is 0.12 to 0.79 inch (3 to 20 mm)
- Lubrication options include dry, grease, and water
- Control of slip ratio between the disks. Testing at ambient temperature is commonly run at slip ratios between 0 and 1 percent; however, the slip ratio is set to 0 percent at temperatures greater than ambient due to complications with thermal expansion of the disks.
- From experience, “runout” (i.e., test completion if failure criteria have not been met) of test samples is considered to be at 10 million cycles for tests conducted at ambient temperature and 2 million cycles for tests conducted at 572 °F (300 °C). Runout has not yet been established for testing at 932 °F (500 °C).

Testing on the thermally controlled twin disk machine has been conducted primarily for proprietary product development and has been limited to three temperature ranges: ambient, 572 °F (300 °C), and 932 °F (500 °C). Repeatability of sample results has not been evaluated, and approximately 20 tests have been performed at elevated temperatures.

The temperature of the wheel disk is controlled by a heating coil that encompasses the wheel disk throughout the testing. Temperature is monitored and recorded using a thermocouple embedded in the wheel disk 0.24 inch (6 mm) below the contact patch. The heating rate is controlled to 92 °F (33.3 °C) per minute. Typical elevated temperature tests involve heating the wheel disk to a target temperature, holding the target temperature for 5 minutes, then cooling the wheel disk back to ambient temperature at a constant rate during a 10-minute cool-down cycle. Water is applied to control the cooling rate. Ambient temperature is maintained for a specific time before the next thermal cycle. This method provides a controlled temperature profile for each thermal cycle and simulates multiple service-braking cycles over the life of the wheel.

3.2 Suggested Test Methodology

TTCI developed the suggested test methodology described in the following section from discussions held between TTCI and NSSMC and NSST, the capabilities of the test machine, and the desire to determine the effects of temperature on shelling and RCF propagation in wheels. All testing will be conducted by NSST in Japan on the thermally controlled twin disk machine owned by NSSMC. The samples will be prepared by NSSMC and cut from a single billet of AAR Class C wheel material to maintain consistency throughout the specimens. The samples will then be heat treated to the specifications used by NSSMC when manufacturing AAR Class C railroad wheels and machined to exact tolerances. Each change in wheel sample requires a change in the rail sample, doubling the total number of samples required to eliminate any variables. Upon completion of the testing the samples will be sectioned in half by NSSMC, and one half will be shipped to TTCI for analysis.

Operating procedures of the twin disk machine are confidential to NSSMC/NSST. The setup and operation was performed during TTCI's visit to the facility, and TTCI took no exceptions to the procedure. To minimize an opportunity for errors, standard practice of NSSMC/NSST dictates that only one employee operates the equipment and uses a documented "checklist" to ensure repeatability. An FTP site will be set up for data transfer of each sample/test.

All testing will be conducted at 1,000 RPM, with a Hertzian contact pressure of 247 ksi (1,700 MPa), and with a slip ratio of 0 percent. Hertzian contact pressure between a wheel and rail in typical North American freight operations is between approximately 200 and 240 ksi, so the test pressure would slightly exceed normal conditions. As explained previously, the slip ratio cannot be controlled effectively during tests with varying temperature. Testing will be conducted without lubrication except for the water used during the cool-down phase of each thermal cycle. To maintain consistency between variables, water will also be applied periodically during ambient temperature testing to match the water application of the elevated temperature tests. Initially, testing will be conducted at ambient, 572 °F (300 °C), and 932 °F (500 °C) with constant rates for temperature increase and decrease, a 5-minute dwell time at the target elevated temperature, and a 5-minute dwell time at ambient temperature before beginning the next thermal cycle.

Each test at the initial three temperatures will be repeated with consistent variables, except the number of cycles. Standard statistical analysis techniques will be used to determine the necessary quantity of test repeats at a given temperature. Following the initial tests conducted at ambient, 572 °F (300 °C), and 932 °F (500 °C) temperatures, a determination will be made about the appropriate intermediate temperatures for additional testing.

RCF initiation and crack propagation rates will be determined for the samples tested at the three initial temperatures. Initiation of RCF will be monitored by periodically stopping the test machine and using visible dye penetrant or visual inspection with photographic evidence. Crack propagation cannot be monitored while the specimen is mounted in the machine. Instead, the samples tested at each of the three initial temperatures will be removed from the test machine and sectioned to determine crack dimensions. Removal and sectioning of these samples will be conducted at different intervals including the number of cycles at which RCF cracks visually appear, the number of cycles required for test completion (i.e., when vibration exceeds 5 g's or runout), and at least one intermediate cycle count.

4. Conclusion

Elevated wheel temperature from tread braking is thought to play a role in promoting RCF initiation and crack propagation. However, the relative effect of elevated temperature on RCF formation has not successfully been quantified with any field testing due to the lack of control and measurement of the operating conditions. Twin disk testing is a well-established means to quickly and cost-effectively investigate the relative effects of different parameters on RCF and wear. The laboratory nature of twin disk testing lends itself well to precise control and measurement of the test conditions. A twin disk test machine with thermal control exists and could be used to quantify the relationship between elevated temperature and RCF damage. Under work conducted in 2014, a test methodology to make use of this machine has been suggested. The proposed test methodology allows for an initial test phase to be conducted at ambient temperature and with thermal cycling to 572 °F (300 °C), and 932 °F (500 °C). Optimal additional test temperatures can be selected using the results of the initial testing.

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Abbreviations and Acronyms

ACRONYMS	EXPLANATION
AAR	Association of American Railroads
FRA	Federal Railroad Administration
NSST	Nippon Steel & Sumikin Technology
NSSMC	Nippon Steel & Sumitomo Metal Corporation
RPM	Revolutions Per Minute
RCF	Rolling Contact Fatigue
TMS	Thermal Mechanical Shelling
T	Tractive Force
TTCI	Transportation Technology Center, Inc.
γ	Slip
WTD	Wheel Temperature Detector