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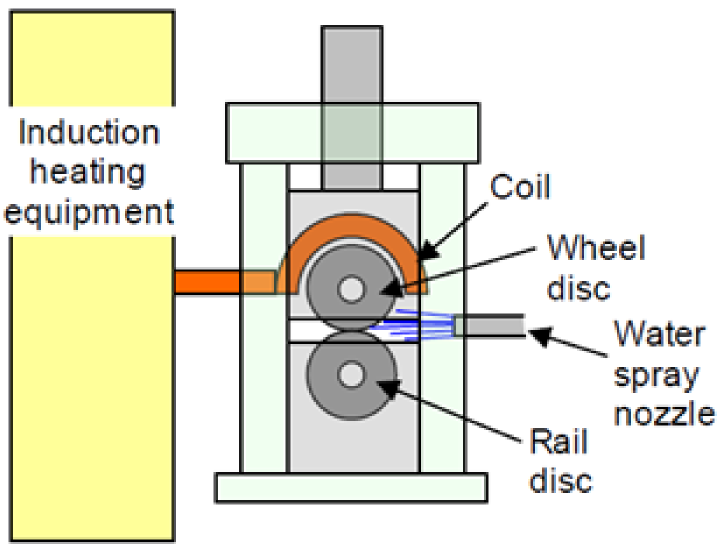
Washington, DC 20590

Rolling Contact Fatigue Testing of Two Different Wheel Steels Under Various Temperatures and Slip Ratios



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14. ABSTRACT
This report presents the results and findings from a testing program conducted to investigate how wheel temperature may affect wheel surface performance, i.e., the development of rolling contact fatigue (RCF) and wear from November 2019. Under this testing program, a twin disc test machine was used to test two different types of wheel steels (i.e., cast and forged) under a range of temperatures (i.e., ambient to 800 °F) and slip ratios from 0 to 0.75 percent. This testing program included a total of 32 tests, covering two types of wheel materials, four different temperatures, four slip ratios, and various traction coefficients as a ratio of longitudinal and vertical wheel/rail contact forces.

15. SUBJECT TERMS
Wheel, rolling contact fatigue, RCF, wear, temperature, slip ratio, traction coefficient, tests

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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

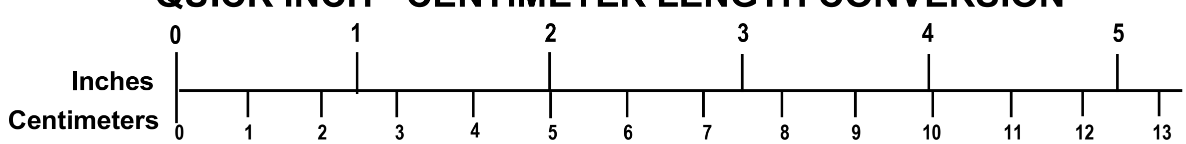
VOLUME (APPROXIMATE)

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)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



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

Acknowledgements

The contributions from Nippon Steel Technology Co., Ltd. and Dr. Takanori Kato to the results and findings presented in this paper are greatly appreciated. The Transportation Technology Center, Inc. (TTCI) engineers, Kerry Jones and Xinggao Shu, were part of the TTCI team that provided the oversight and guidance to this testing program.

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Executive Summary

On November 2019, the Federal Railroad Administration contracted Transportation Technology Center, Inc. to develop the test plan and manage the entire program, while Nippon Steel Technology Co., Ltd. (NSTEC) conducted all the lab testing using the twin disc test machine to investigate how wheel temperature affects wheel surface performance (i.e., development of rolling contact fatigue [RCF] and wear). Testing was completed with two different types of wheel steels (i.e., cast and forged) under a range of temperatures, ambient to 800 °F, and slip ratios from 0 to 0.75 percent. This testing program included a total of 32 tests, covering two types of wheel materials, four different temperatures, four slip ratios, and various traction coefficients as a ratio of longitudinal and vertical wheel/rail contact forces.

Test results showed that the number of loading cycles required to generate RCF (i.e., RCF life) decreased with the increase of the traction coefficient at all temperatures for both cast and forged wheel steels. However, the effect of traction coefficient appeared more significant at ambient and 300 °F than at 600 °F and 800 °F. RCF life of wheels also decreased with the increase of wheel temperature at the lowest traction coefficient. At other traction coefficients, however, wheel temperature did not appear to have much effect on RCF life.

Results indicated that the wear rate of wheels increased with the increase of traction coefficient at all temperature conditions. The increase of wear rate at 800 °F, however, was lower than at other temperatures. No significant difference of wear rate was observed between the cast and forged wheel steels. Wear rate increased with the increase of wheel temperature at the largest traction coefficient of 0.30. At other traction coefficients, wear rate was not affected by wheel temperature.

Finally, the tests showed that the traction coefficient had more effect on RCF life and wear rate of the wheels than the temperature under the testing scenarios considered.

1. Introduction

This report presents the results and findings from a testing program that was conducted by Transportation Technology Center, Inc. (TTCI) and Nippon Steel Technology Co., Ltd. (NSTEC) on November 2019 to investigate how wheel temperature may affect wheel surface performance (i.e., development of rolling contact fatigue [RCF] and wear). A twin disc test machine was used to test two different types of wheel steels (i.e., cast and forged) under a range of temperatures (ambient to 800 °F) and slip ratios from 0 to 0.75 percent. This testing program included a total of 32 tests, covering 2 types of wheel materials, 4 different temperatures, 4 slip ratios, and various traction coefficients as a ratio of longitudinal and vertical wheel/rail contact forces.

1.1 Background

Impact wheel loads above 400 kN are the primary cause for wheelset removals in the North American freight railroad industry. The impact loads generated by the wheels can also affect other components of rolling stock such as roller bearings, as well as track components (e.g., rail). The source of impact loads has been studied extensively, and it is generally agreed that wheel spalling and shelling contribute to the problem of impact loads [1]–[4].

Shelling is a fatigue process, often generated from RCF on the wheels [4–5] in which cracks initiate at or near the tread surface of the wheel and propagate until pieces of the wheel tread surface break out. Both material strength and residual stress are thought to be important factors in a wheel's ability to resist damage from RCF [6] [7]. These properties can be affected by changes in temperature.

Twin disc roller machines have been used for decades in the laboratory to study RCF [8] [9]. A twin disc roller machine consists of two rollers that are pressed together while the discs are rotated to simulate wheel/rail contact. One disc represents the wheel and the other disc represents the rail. Such machines can provide fast, cost-effective results due to relatively small size of the discs and their continuous rolling action. Using twin disc roller machines, the effects of contact pressure, slip ratio, and lubrication on the development of RCF cracks have been studied by many researchers. Recently, the owner of a twin disc roller machine added an induction heating coil to control the temperature of the "wheel" disc [10]. This twin disc roller machine provides an ideal test environment to quantify the relationship between wheel temperature and the number of load cycles required to generate RCF (i.e., RCF life of wheel).

1.2 Objectives

The objective of this testing program was to investigate wheel performance in terms of the resistance to RCF and wear under various temperatures and slip ratios for two types of freight car wheel steels: cast and forged steels using a twin disc RCF testing machine developed by NSTEC, while TTCI conducted the earlier work [11]–[13].

1.3 Overall Approach

Wheel discs machined from the cast and forged wheels from freight cars in North America were tested with the twin disc machine, until occurrences of RCF, under various wheel temperatures and slip ratios. The effects of elevated temperature and slip ratio on RCF live of wheel specimens were assessed based on the test results obtained.

1.4 Scope

Results and findings reported in this document were specific to the specimens prepared under this testing program, using the testing machine described, and with the test variables considered. Neither modeling, nor full-scale testing programs were conducted to collaborate the results obtained under this laboratory testing.

1.5 Organization of the Report

Section 1 introduces the testing program. Section 2 describes the testing method and test matrix. Section 3 presents the test results and findings. Section 4 summarizes the work performed and its completion. Appendix A includes the test data for all the 32 tests conducted.

2. Testing Method and Testing Matrix

This section documents the wheel and rail test specimens used for this project, as well the testing procedure applied to all 32 tests.

2.1 Wheel and Rail Test Specimens (Discs)

The wheel discs used in this testing were Association of American Railroads' (AAR) Class C wheel steels, both cast and forged, from the wheels used in the North American freight railway industry. Hardness of all wheel discs were measured in terms of Rockwell hardness (HRC). Measured positions were along the center line between the inner and outer diameters on the side surfaces of the disc, as shown in Figure 1. There were five measured positions per disc.

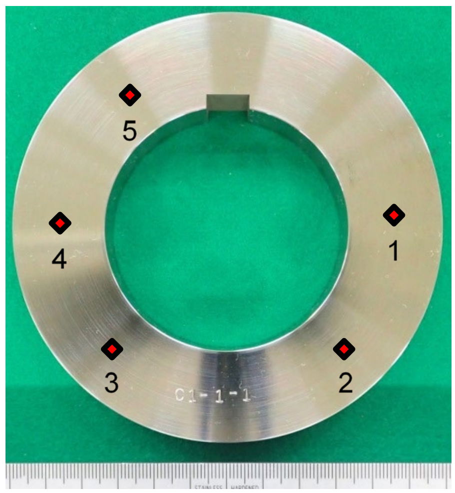


Figure 1. Measurement Positions of Rockwell Hardness on Wheel Disc

The average Rockwell hardness of all tested wheel discs was HRC 35.0—or Brinell hardness (HB) 327—for the cast steel, and HRC 31.7 (HB 299) for the forged steel.

The rail discs used in testing were 0.7 percent C steel with pearlite structure, which is like Class C wheel steel. The average Rockwell hardness of the tested rail discs was HRC 38.3 (HB 356). This hardness was higher than what is required for the intermediate strength rails (HB 350), but lower than what is required for the high strength rails (HB 370) for applications in North America.

Because a rail disc diameter of 200 mm is required in twin disc testing, steel materials equivalent to the high strength rail for this size were not easily available for the preparation of the rail discs as the actual rail heads are smaller than the rail disc size. Test results of RCF life of wheel discs could be different if the high strength rail material was used as the rail discs. However, for the effects of elevated temperature and slip ratio, the hardness of the rail discs used was considered adequate.

Table 1 shows the mechanical properties of the rail disc material used. Again, these properties indicate that the rail discs had properties like those of the intermediate strength rails.

Table 1. Mechanical Properties of Rail Disc Material

Yield Stress	Ultimate Tensile Strength	Elongation (%)	Reduction of Area (%)
693 MPa	1,035 MPa	17.6	47.4

2.2 Test Disc

Wheel discs were cut from the area close to the actual wheel tread (see Figure 2). Rail discs were taken from roughly cut wheel materials after quenching and tempering. Figure 3 shows the dimensions of both the wheel and rail test discs—the wheel disc was 120 mm in diameter, and the rail disc was 200 mm in diameter. The contact width of the discs is 5 mm with a flat-shaped surface at the cross section. Thermocouples were embedded 6 mm deep from the outer surface of wheel disc to measure wheel temperature during testing. Figure 4 provides photos of the test discs.

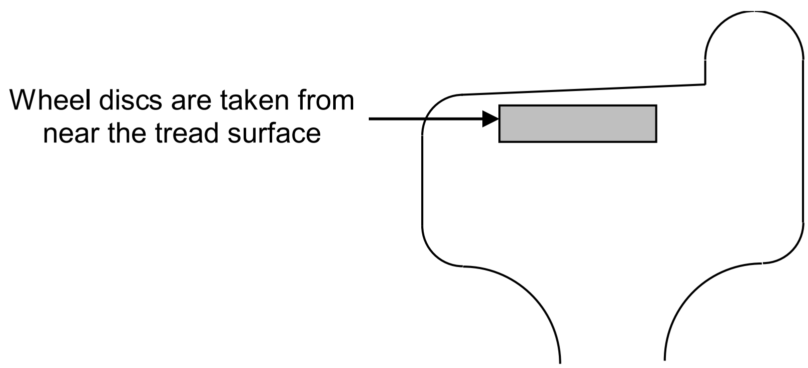
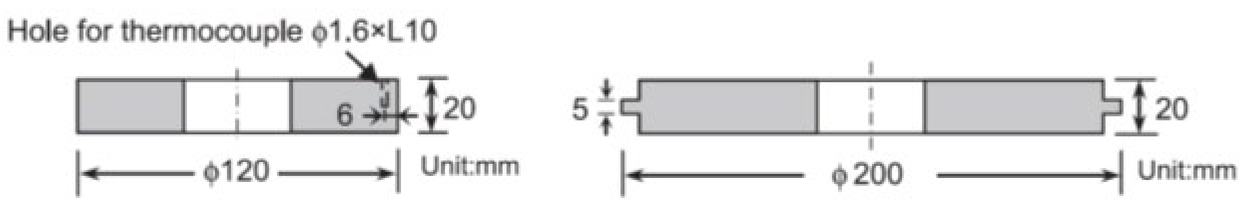
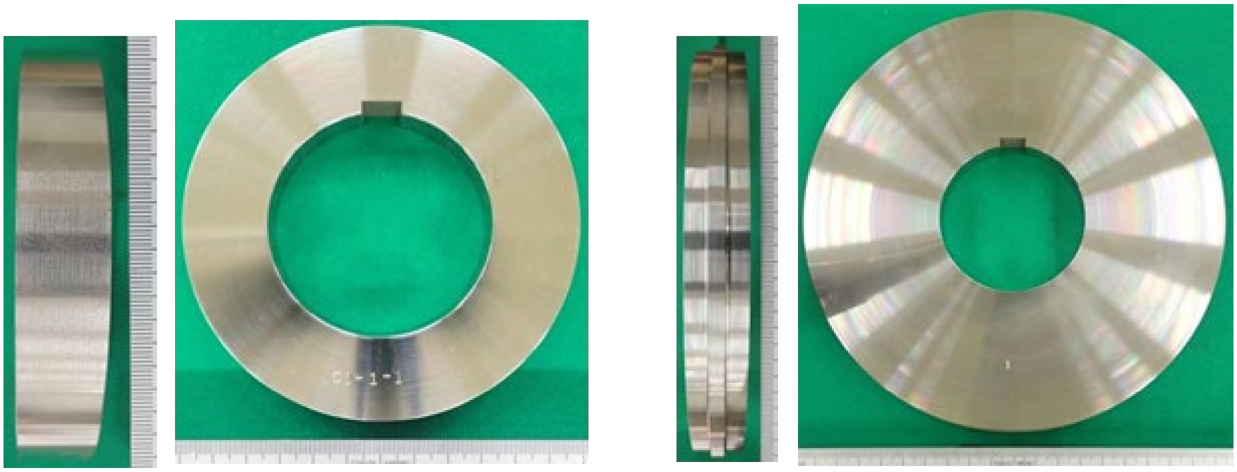


Figure 2. Schematic of Wheel Disc Sampling Position



(a) Wheel Disc **(b) Rail Disc**

Figure 3. Schematic of Wheel and Rail Test Discs



(a) Wheel Disc (b) Rail Disc

Figure 4. Photos of Wheel and Rail Test Discs

2.3 Testing Procedure

Figure 5 illustrates the twin disc test machine. Induction heating was applied to elevate the temperature of the wheel disc during testing. For each test, the vertical load was 7.8 kN, corresponding to a Hertzian contact stress of 1,200 MPa.

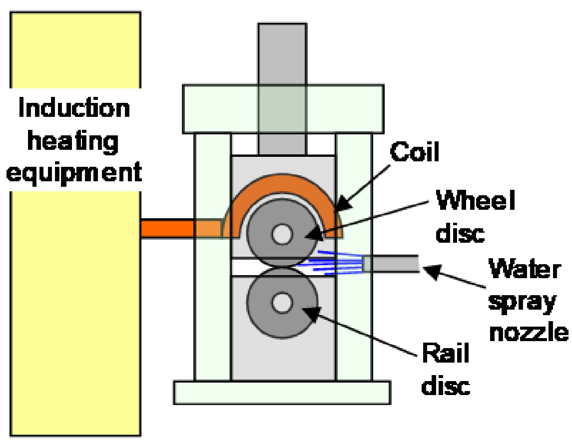


Figure 5. Schematic of the Twin Disc Testing Machine

Table 2 lists all 32 tests conducted. The test matrix included two types of wheel steels, four different wheel temperatures, and four different slip ratios (S_R). The slip ratio is defined in Equation 1.

$$S_R = \frac{(V_R - V_W)}{(V_R + V_W)/2} \times 100 \qquad (1)$$

Where:

V_R is the rotation speed of the rail disc, and V_W is the rotation speed of the wheel disc.

For any test, the wheel disc was set at a rotation speed of 700 rpm, but the rotation speed of the rail disc was adjusted to achieve a target slip ratio. The rotation speeds of the wheel and rail discs remained constant during each test, although the wheel disc may have experienced a change in diameter due to thermal expansion under elevated temperature.

Vertical load was measured by a load cell mounted on the bearing. Traction was measured by a torque meter mounted on the wheel disc axle. K-type thermocouples were used for measurement of wheel disc temperature. Vertical load was applied by a hydraulic cylinder. Wheel and rail discs were driven independently by two electrical motors.

For a given test, the temperature and wet/dry condition of wheel disc were varied, as illustrated in Figure 6. During each thermal cycle, elevated temperature was held for 5 minutes for all tests. Water was supplied after cooling the wheel disc to room temperature to accelerate crack propagation while discs were rotating under loaded contact. Air was used to avoid rapid cooling. Flow rate of air was 0.0024 Nm^3/min, and flow rate of water was 1 L/min. Duration of the air cooling was 5 minutes, and water was supplied for 10 minutes in a 35-minute thermal cycle. The temperatures of air and water were not controlled, and they were essentially room temperature.

Accelerometers installed on the bearing were used to detect vibrations that might be early indicators of RCF damage. RCF life was defined as the number of load cycles when the vibration of the testing machine exceeded 20 m/s^2. A test would be stopped when the vibration exceeded 25 m/s^2. The maximum number of load cycles, however, was set at 2×10^6 cycles, even if RCF damage did not occur. One load cycle is equivalent to one turn of wheel disc.

Data was gathered continuously while the testing machine was running. All channels were sampled at 500 Hz, and the average value of the sampled data over each minute was used for further analysis.

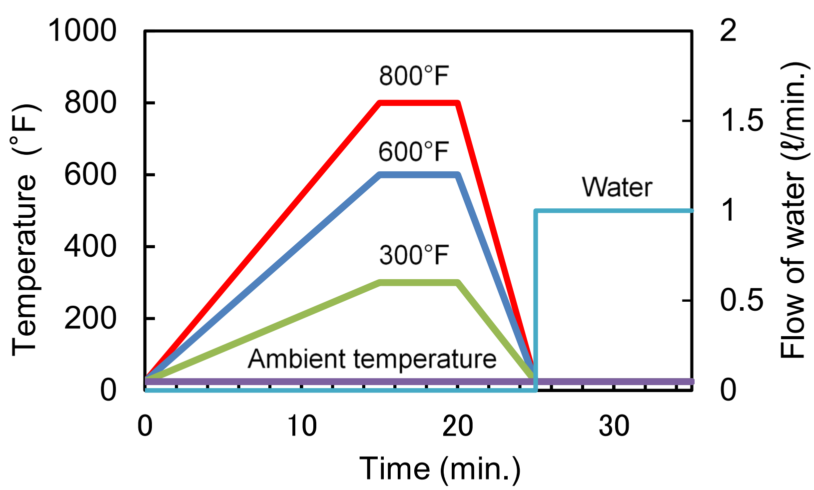


Figure 6. Thermal Cycle of Wheel Disc and Variation of Water Flow

Table 2. Test Matrix

Test ID	Specimen	Temperature	Slip Ratio	Revolution (rpm)	
				Wheel	Rail
1	Forged	Ambient	0%	700	420.0
17	Cast				
2	Forged	300 °F	0%	700	420.0
18	Cast				
3	Forged	600 °F	0%	700	420.0
19	Cast				
4	Forged	800 °F	0%	700	420.0
20	Cast				
5	Forged	Ambient	0.25%	700	421.05
21	Cast				
6	Forged	300 °F	0.25%	700	421.05
22	Cast				
7	Forged	600 °F	0.25%	700	421.05
23	Cast				
8	Forged	800 °F	0.25%	700	421.05
24	Cast				
9	Forged	Ambient	0.5%	700	422.10
25	Cast				
10	Forged	300 °F	0.5%	700	422.10
26	Cast				
11	Forged	600°F	0.5%	700	422.10
27	Cast				
12	Forged	800 °F	0.5%	700	422.10
28	Cast				
13	Forged	Ambient	0.75%	700	423.15
29	Cast				
14	Forged	300 °F	0.75%	700	423.15
30	Cast				
15	Forged	600 °F	0.75%	700	423.15
31	Cast				
16	Forged	800 °F	0.75%	700	423.15
32	Cast				

3. Results

This section outlines the results for all 32 tests, while Appendix A contains more in-depth data. This also provides the test matrix listed in Table 1 that were obtained with a slip ratio of 0.25 percent to illustrate the analysis of the test results.

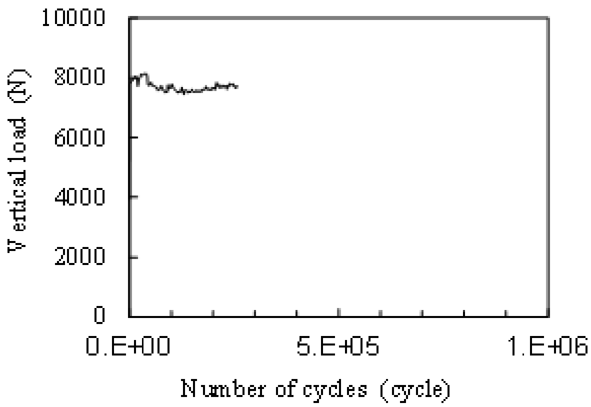
3.1 Test at Ambient Temperature with 0.25 Percent Slip Ratio

Vertical load was almost constant during the test. Figure 7 shows time histories of vertical load, torque of wheel disc, wheel disc temperature, and vibration acceleration of the testing machine using the cast steel at ambient temperature with 0.25 percent slip ratio (Test ID 21). Average Hertzian stress calculated from the Hertzian theory was 1,217 MPa. The torque of wheel disc changed with the load cycle—this was considered an effect of alternating dry and wet conditions, particularly when the contact surface roughness increased. The vibration acceleration of the machine rapidly increased when RCF damage occurred.

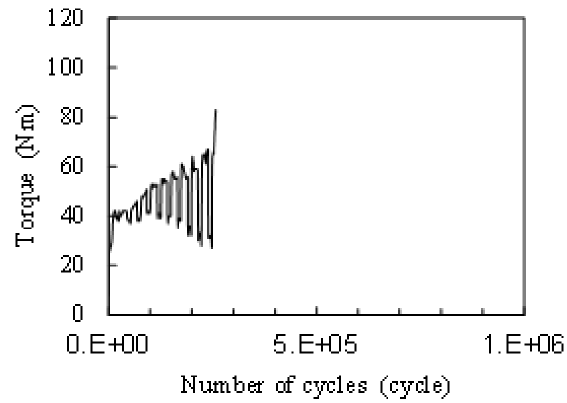
Figure 8 shows the contact surfaces of the wheel and rail discs after testing. The wheel disc had obvious fatigue damage at the contact surface. The rail disc, on the other hand, had a relatively clean surface.

Figure 9 shows the profiles of the contact surfaces of the wheel and rail discs. The profiles of the contact surfaces of both the wheel and rail discs changed due to wear.

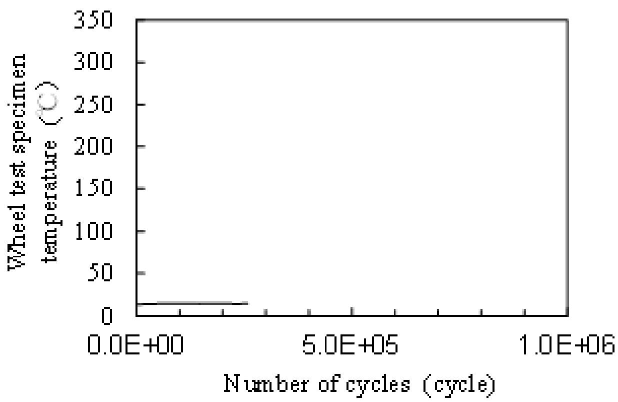
Results of the forged steel under the same test conditions were similar for the cast steel.



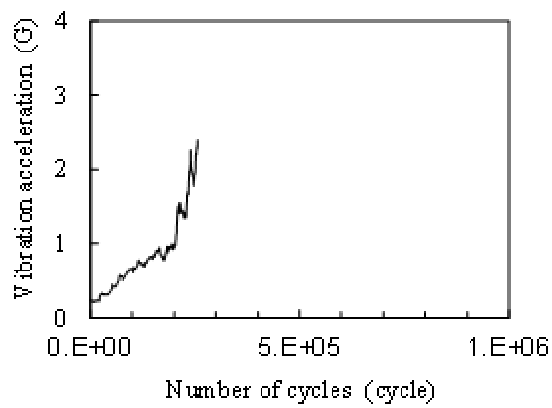
(a) Vertical load



(b) Torque of wheel disc

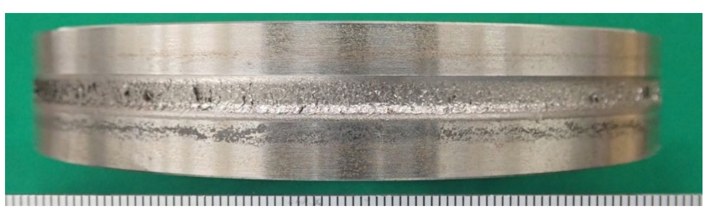


(c) Wheel disc temperature

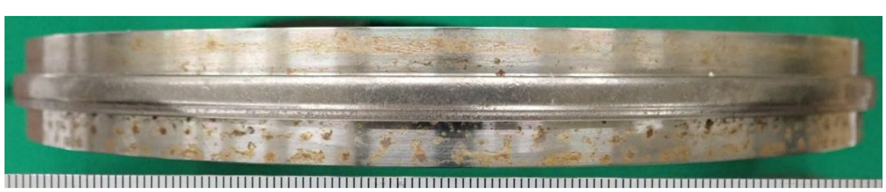


(d) Vibration acceleration of testing machine

Figure 7. Time Histories of Measurements
(Cast Steel at Ambient Temperature with 0.25 Percent Slip Ratio)



(a) Wheel disc



(b) Rail disc

Figure 8. Photos of Test Discs
(Cast Steel at Ambient Temperature with 0.25 Percent Slip Ratio)

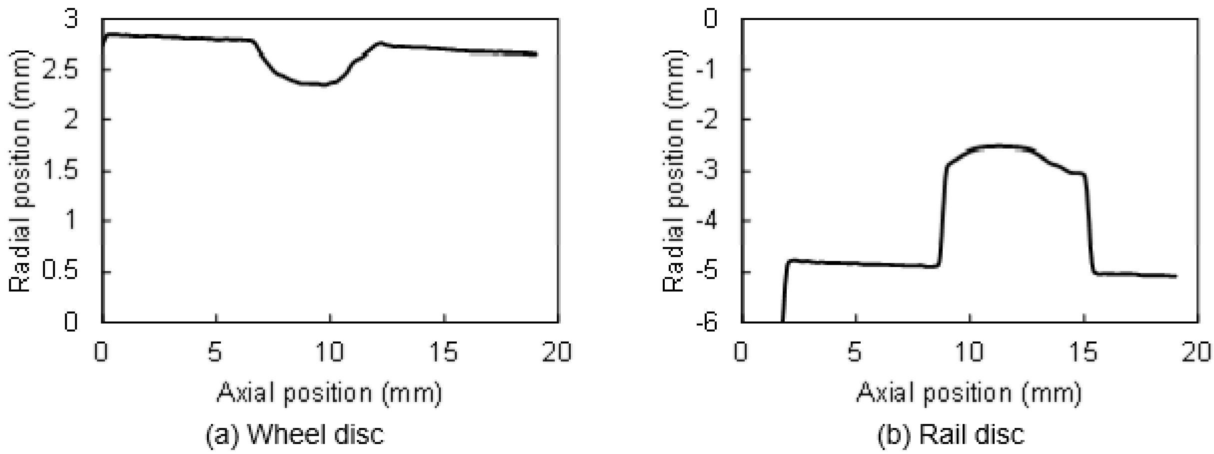


Figure 9. Contact Surface Profiles of Test Discs
(Cast Steel at Ambient Temperature with 0.25 Percent Slip Ratio)

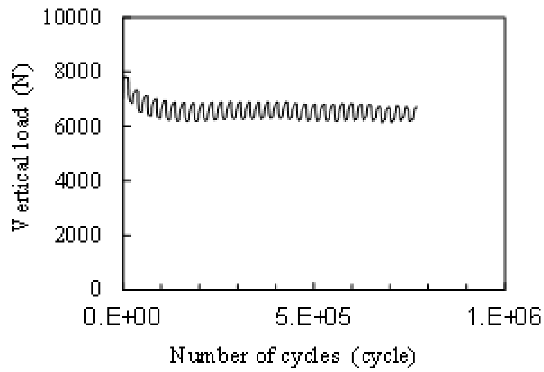
3.2 Test at 300 °F with 0.25 Percent Slip Ratio

Figure 10 shows time histories of vertical load, torque of wheel disc, wheel disc temperature, and vibration acceleration of testing machine using cast steel at 300 °F, with 0.25 percent slip ratio (Test ID 22). The vertical load slightly varied during the test—this was caused by the change of wheel disc temperature. The range of variation was approximately 4 percent, and this was thought to have a minor effect on RCF life. Average Hertzian stress calculated from the Hertzian theory was 1,125 MPa. The torque of wheel disc varied and was caused by change in the wheel disc temperature (i.e., the diameter of wheel disc changed with the temperature). The temperature of the wheel disc was well controlled during the test. The vibration acceleration of the test machine rapidly increased when RCF damage occurred.

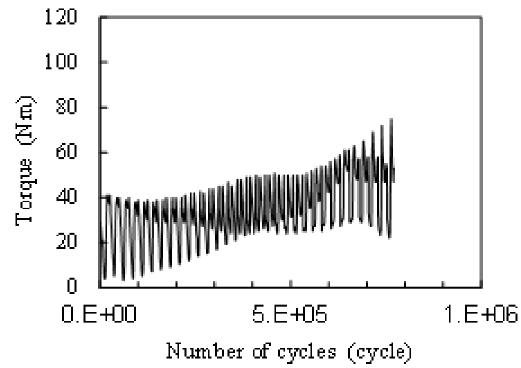
Figure 11 shows photos of the contact surfaces of the wheel and rail discs after the test. The wheel disc had severe fatigue damage at the contact surface, whereas, the rail disc had a clean surface.

Figure 12 shows the contact surface profiles of the wheel and rail discs; both profiles changed due to wear.

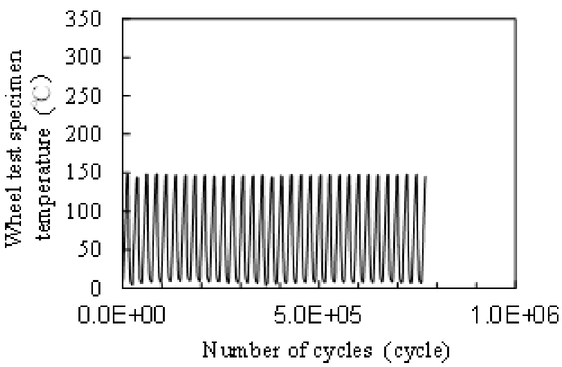
Results of the forged steel under the same test conditions were like the results of the cast steel.



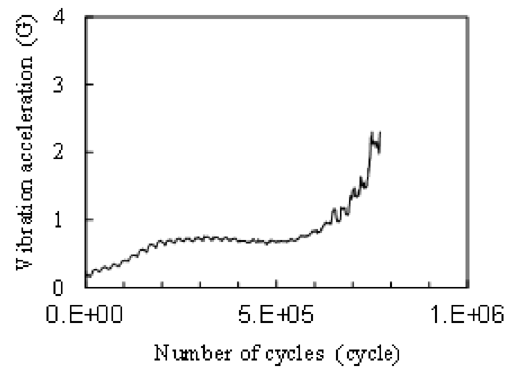
(a) Vertical load



(b) Torque of wheel disc

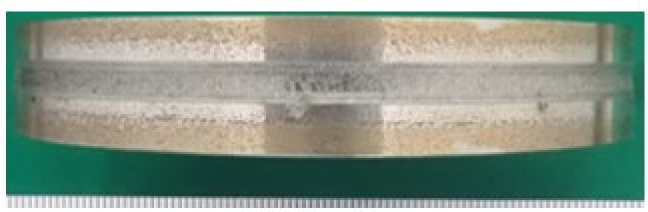


(c) Wheel disc temperature

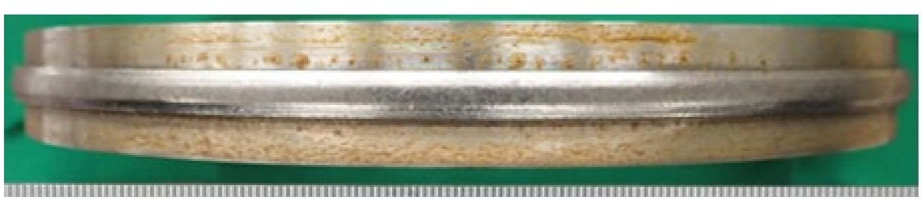


(d) Vibration acceleration of testing machine

Figure 10. Time Histories of Measurements
(Cast Steel at 300 °F with 0.25 Percent Slip Ratio)



(a) Wheel disc



(b) Rail disc

Figure 11. Photos of Test Discs
(Cast Steel at 300 °F with 0.25 Percent Slip Ratio)

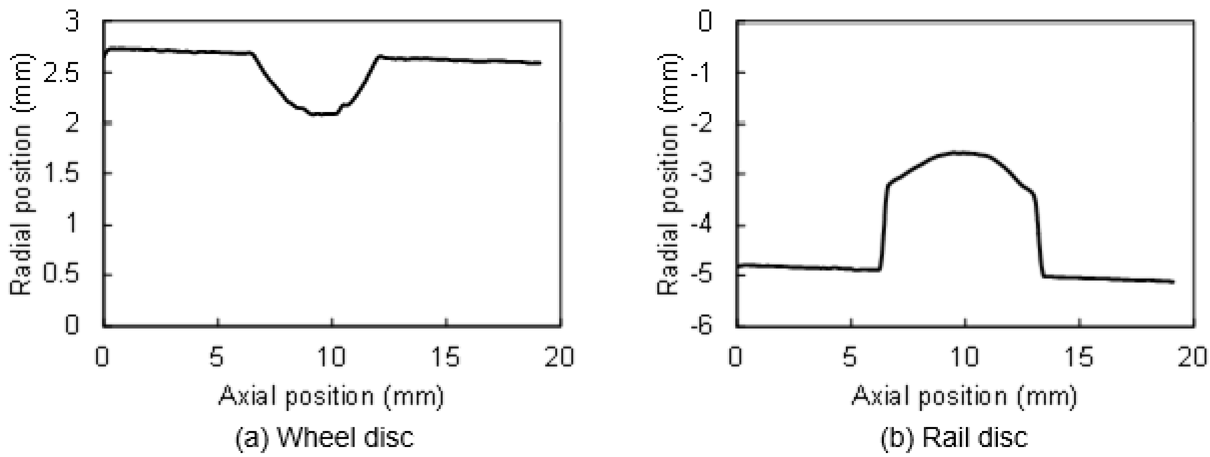


Figure 12. Contact Surface Profiles of Test Discs
(Cast Steel at 300 °F with 0.25 Percent Slip Ratio)

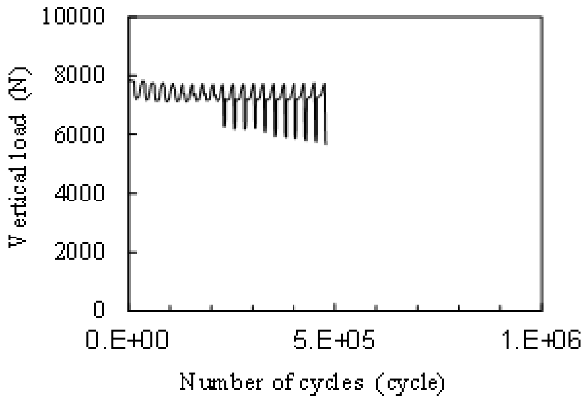
3.3 Test at 600 °F with 0.25 Percent Slip Ratio

Figure 13 shows time histories of vertical load, torque of wheel disc, wheel disc temperature, and acceleration using the cast steel at 600 °F with 0.25 percent slip ratio (Test ID 23). The vertical load varied during the test, and was approximately 9 percent, which was larger than that for the test at 300 °F. This was because the increase of wheel disc temperature was larger in this test. The average Hertzian stress calculated from the Hertzian theory was 1,183 MPa. The torque of wheel disc varied while testing and was larger than the test at 300 °F. Moreover, the torque showed a negative value under this test condition. This indicated that the direction of longitudinal force reversed from the tests conducted at 300 °F and at ambient temperature. The vibration acceleration of the machine rapidly increased when RCF damage occurred.

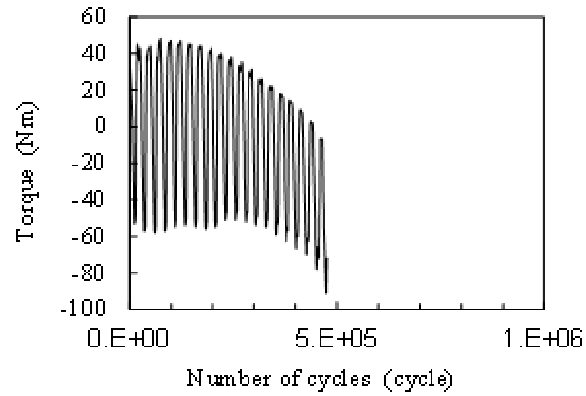
Figure 14 shows the contact surfaces of the wheel and rail discs after the test. The wheel disc had minor fatigue damage at the contact surface, whereas, the rail disc had severe fatigue damage. This may have been caused by the reversed direction of longitudinal force.

Figure 15 shows the profiles of the contact surfaces of the wheel and rail discs. The change of profiles was relatively small.

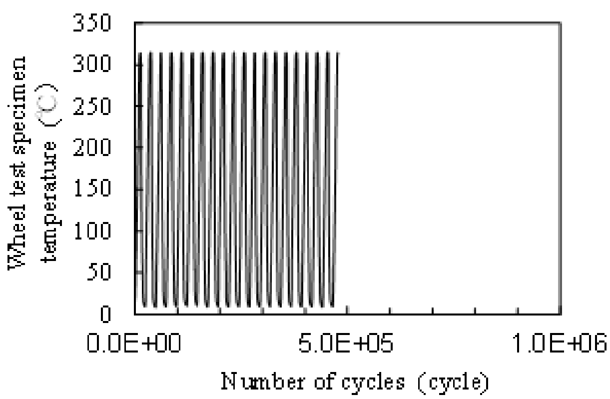
Results of the forged steel under the same test condition were like that of the cast steel.



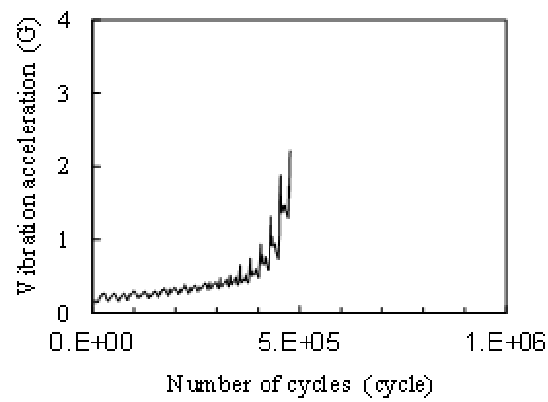
(a) Vertical load



(b) Torque of wheel disc

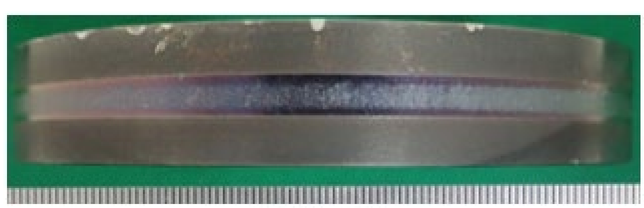


(c) Wheel disc temperature

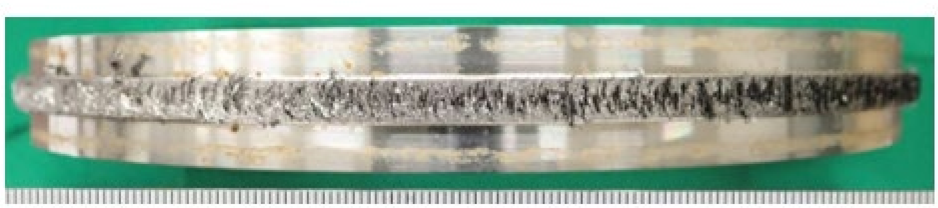


(d) Vibration acceleration of testing machine

Figure 13. Time Histories of Measurements (Cast Steel at 600 °F with 0.25 Percent Slip Ratio)



(a) Wheel disc



(b) Rail disc

Figure 14. Photos of Test Discs

(Cast Steel at 600 °F with 0.25 Percent Slip Ratio)

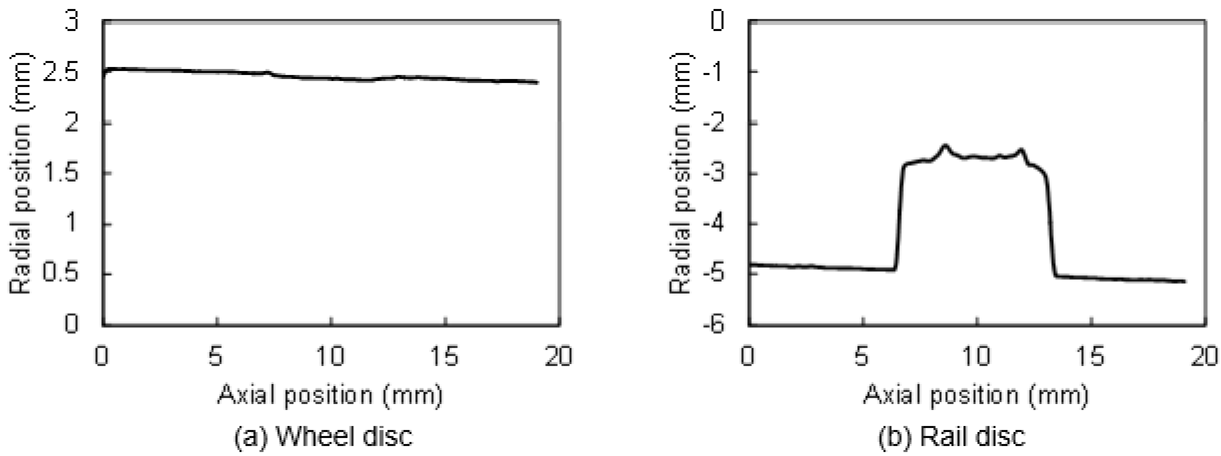


Figure 15. Contact Surface Profiles of Test Discs
(Cast Steel at 600 °F with 0.25 Percent Slip Ratio)

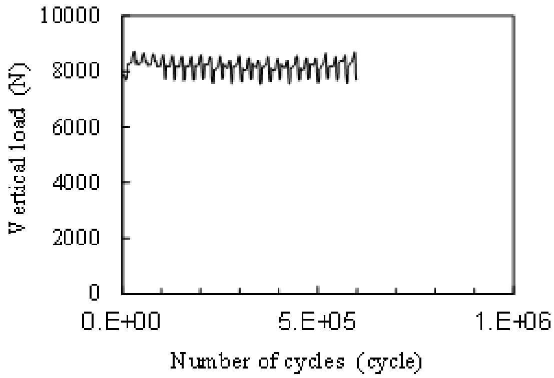
3.4 Test at 800 °F with 0.25 Percent Slip Ratio

Figure 16 shows time histories of vertical load, torque of wheel disc, wheel disc temperature, and acceleration for the test using the cast steel at 800 °F with 0.25 percent slip ratio (Test ID 24). The vertical load varied during the test and was approximately 12 percent, which was larger than the test at 600 °F, because the increase of wheel disc temperature was larger in this test. Average Hertzian stress calculated from the Hertzian theory was 1,253 MPa. The torque of wheel disc varied significantly during testing. This variation was larger than that at 600°F. The torque showed both positive and negative values as the direction of longitudinal force changed during testing. The temperature of the wheel disc was well-controlled. The vibration of acceleration of machine rapidly increased when RCF damage occurred.

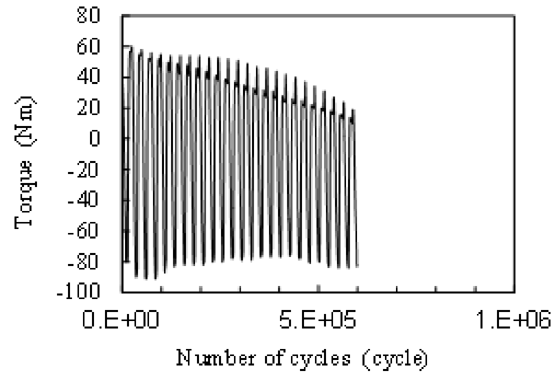
Figure 17 shows the contact surfaces of the wheel and rail discs after test. The wheel disc had severe fatigue damage at the contact surface, whereas, the rail disc had only minor fatigue damage.

Figure 18 shows the profiles of the contact surfaces of the wheel and rail discs. Wear depths of the discs were larger than those tested at 600 °F.

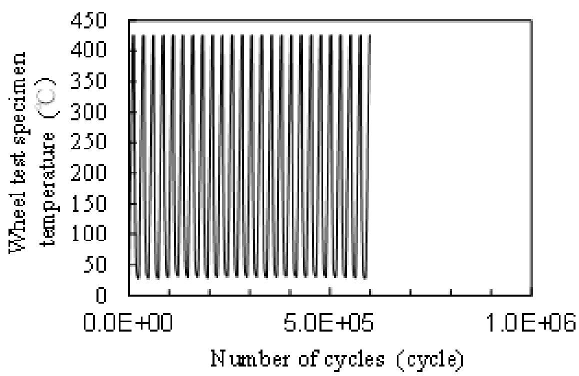
Results of the forged steel under the same test condition were similar that of the cast steel.



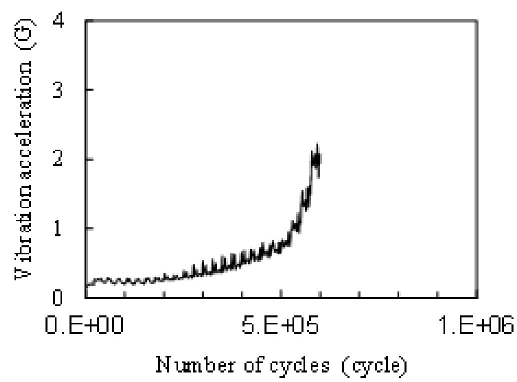
(a) Vertical load



(b) Torque of wheel disc

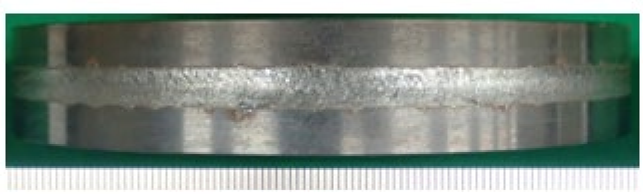


(c) Wheel disc temperature

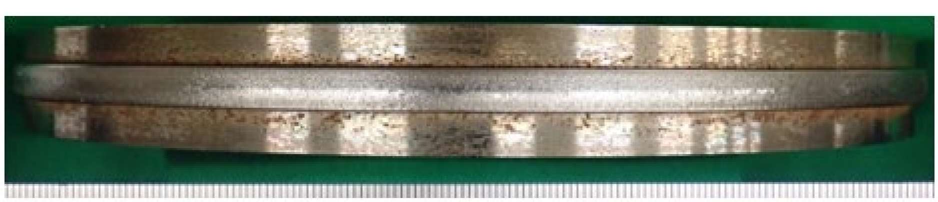


(d) Vibration acceleration of testing machine

Figure 16. Time Histories of Measurements
(Cast Steel at 800 °F with 0.25 Percent Slip Ratio)



(a) Wheel disc



(b) Rail disc

Figure 17. Photos of Test Discs
(Cast Steel at 800 °F with 0.25 Percent Slip Ratio)

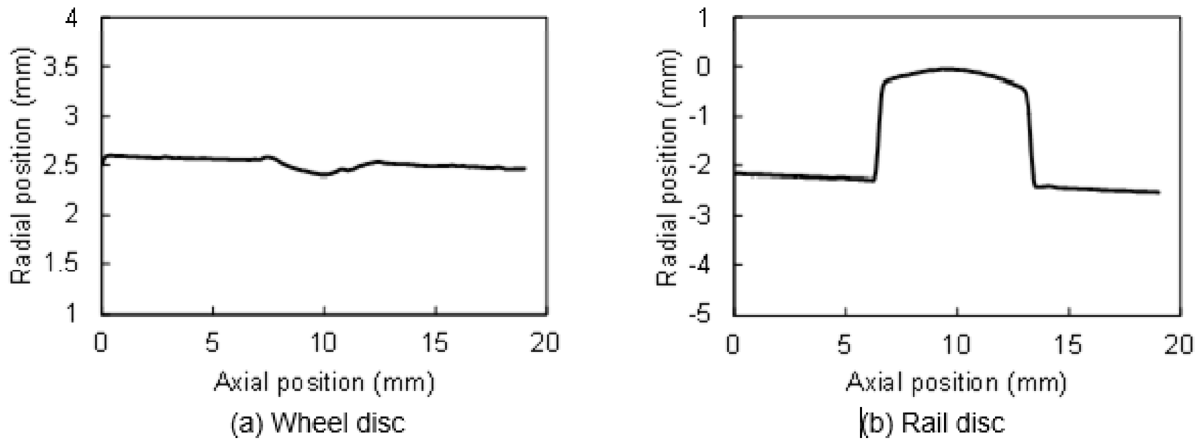


Figure 18. Contact Surface Profiles of Test Discs
(Cast Steel at 800 °F with 0.25 Percent Slip Ratio)

3.5 Rolling Contact Fatigue Life

Figure 19 shows the results of RCF life of the wheel and rail discs as a function of traction coefficient. Traction coefficient was calculated as the average ratio of the longitudinal force obtained from the measured torque over the vertical force. The increase of vibration to detect RCF damage may include the influence of uneven wear of a test disc. However, RCF damage was the dominant factor for the increase of vibration when vibration rapidly increased toward the end of the disc life. If wear were the main cause of the increase of vibration, it would only increase slightly during testing.

As shown, RCF life of the discs decreased with the increase of traction coefficient at all temperatures and for both wheel steel materials. However, the effect of traction coefficient was larger at the ambient temperature and at 300 °F than at 600 °F and 800 °F. In the case of negative traction coefficient, RCF damage occurred on the surface of the rail disc.

Figure 20 shows RCF life of wheel discs as a function of wheel temperature. RCF life were categorized by values of traction coefficient. As shown, RCF life decreased with the increase of wheel disc temperature at the lowest traction coefficient. At the other traction coefficients, however, the wheel disc temperature had minimal effect on the RCF life. These results suggested that the traction coefficient had more effect on the RCF life of the wheel discs than temperature in this test scenarios considered.

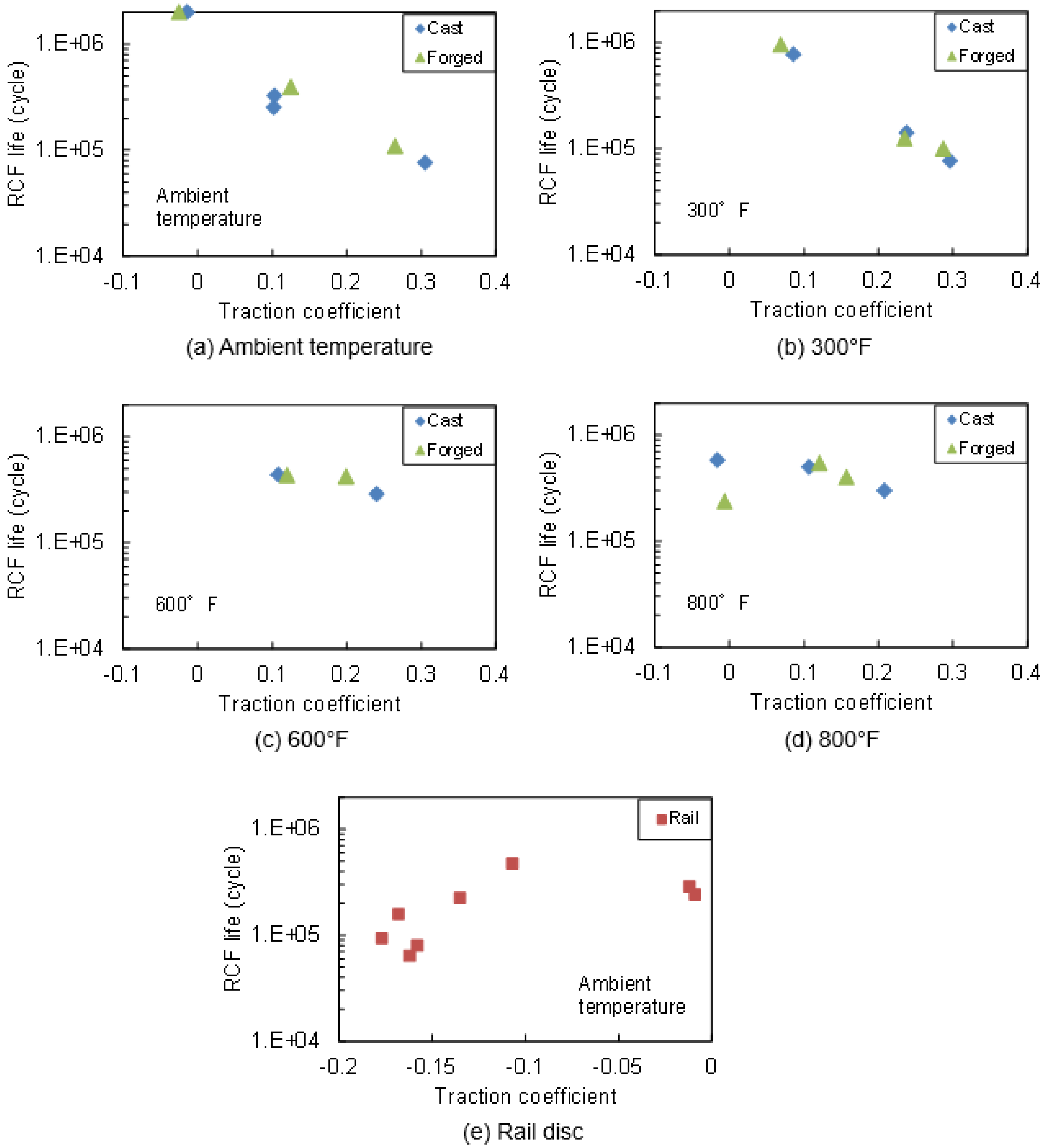


Figure 19. RCF Life as a Function of Traction Coefficient

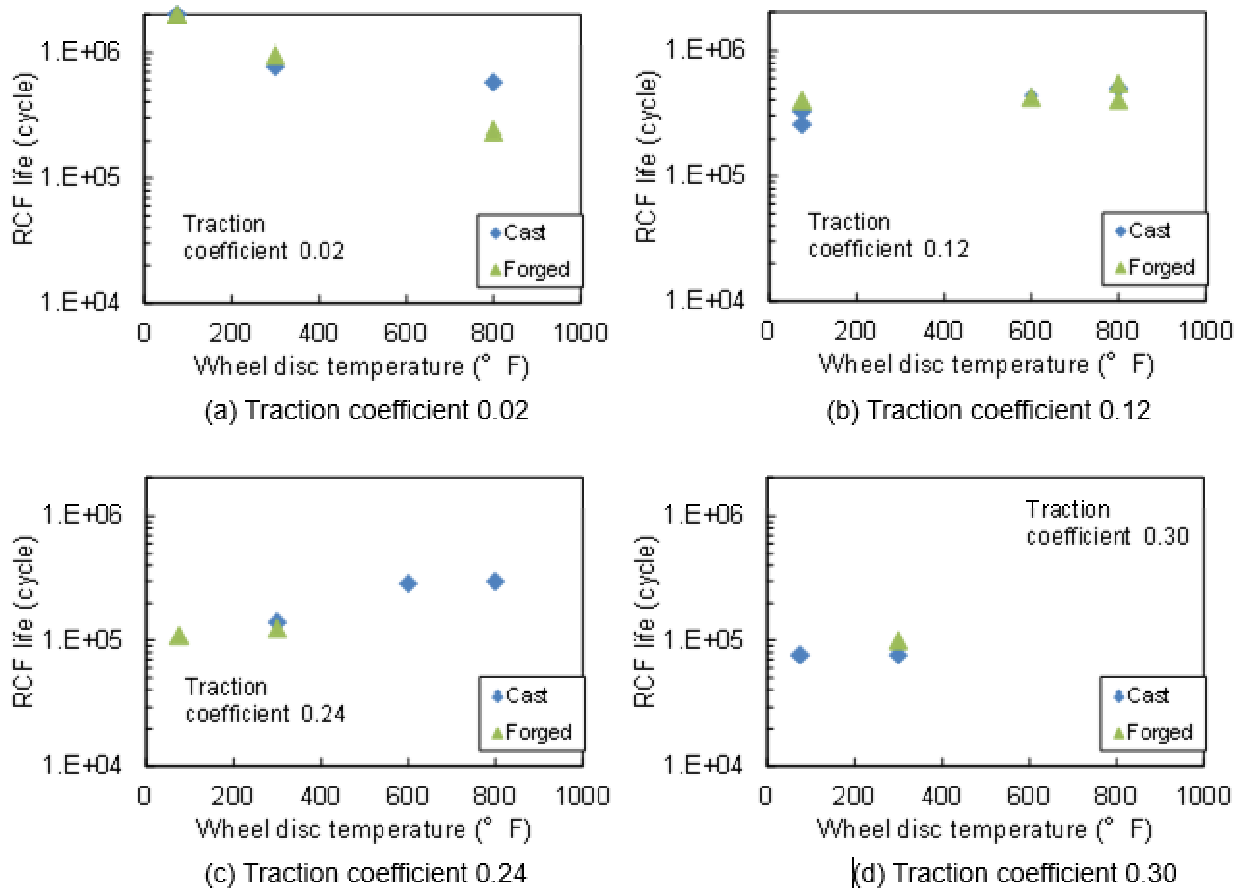


Figure 20. RCF Life as a Function of Wheel Disc Temperature

3.6 Wear

Figure 21 shows wear rate test results of wheel and rail discs as a function of traction coefficient. Wear rate was calculated as the ratio of weight loss of disc over the rolling distance. As shown, wear rate of wheel discs increased with the increase of traction coefficient at all temperatures. However, the increase of wear rate at 800 °F was lower than the increase at other temperatures. There were no significant differences of wear rate between the cast and forged steels. Wear rate of rail discs also increased with the increase of traction coefficient, although there was significant variation of wear rate test results for the rail discs.

Figure 22 shows wear rate test results of wheel discs as a function of wheel disc temperature. Wear rates were categorized by the traction coefficients. Wear rate increased with the increase of wheel disc temperature at the traction coefficient of 0.30. At other traction coefficients, however, wear rate was not affected by wheel disc temperature. These results indicated that the traction coefficient had more effects on the wear rate than temperature in this test scenarios.

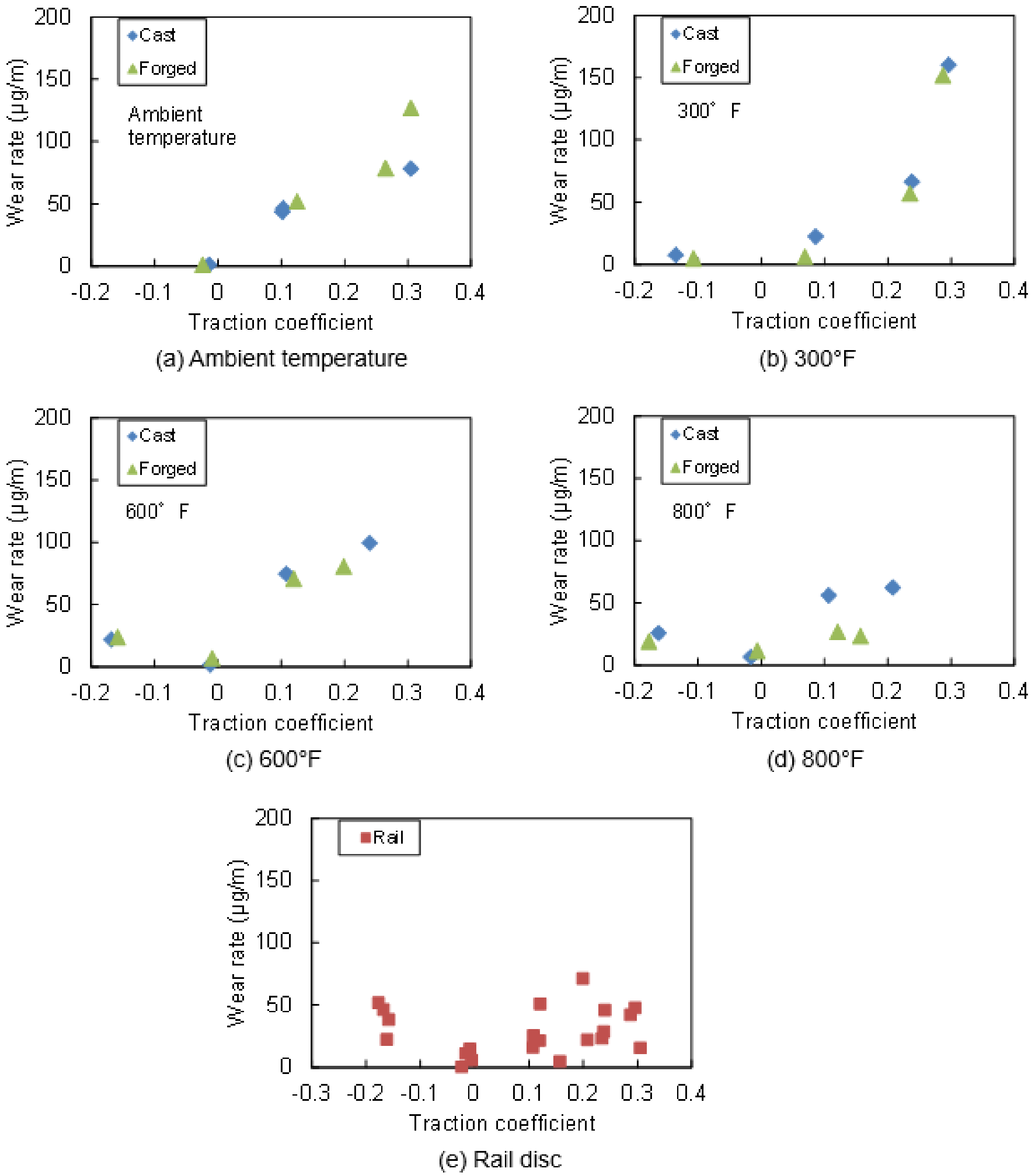


Figure 21. Wear Rate as a Function of Traction Coefficient

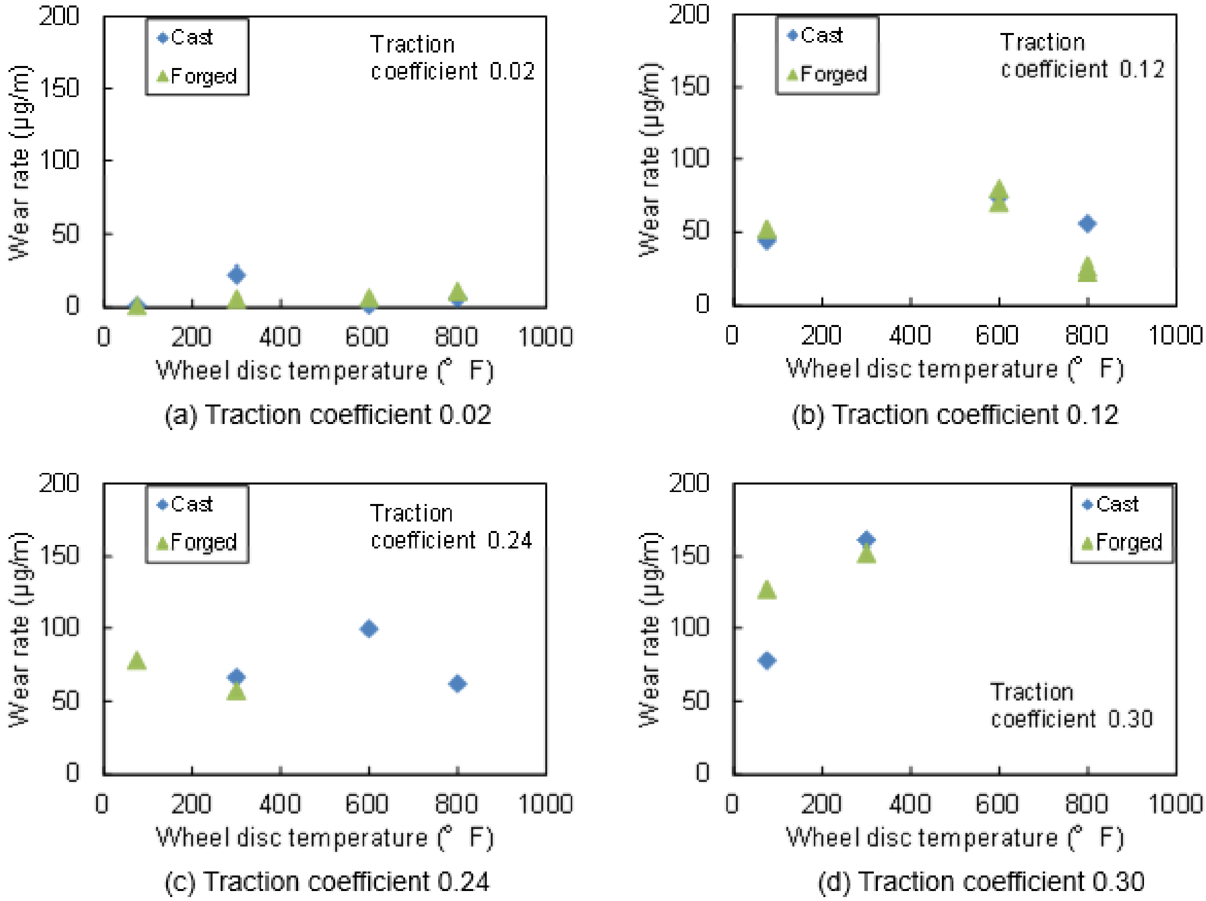


Figure 22. Wear Rate as a Function of Wheel Disc Temperature

4. Conclusion

On September 2019, the Federal Railroad Administration contracted TTCI and NSTEC to investigate how wheel temperature affects wheel surface performance (i.e., the development of RCF and wear). During testing, RCF life of the wheel discs decreased with the increase of traction coefficient at all temperatures and for both cast and forged wheel steels. Traction coefficient had a larger effect on the RCF life of wheel discs at ambient temperature and 300 °F than at 600 °F and 800 °F. In the case of negative traction coefficient, RCF damage occurred on the rail discs.

RCF life of wheel discs decreased with the increase of wheel temperature at the lowest traction coefficient. At other traction coefficients, wheel disc temperature had no significant effect on the RCF live of wheel discs.

Wear rate of wheel discs increased with the increase of traction coefficient at all temperatures. The increase of wear rate at 800 °F was lower than increases at other temperatures. There was no significant difference of wear rates of the discs between the cast and forged wheel steels.

Wear rate of wheel discs increased with the increase of wheel disc temperature at the largest traction coefficient of 0.30. At other traction coefficients, wear rates of wheel discs were not affected by wheel disc temperature.

Test results indicated that the traction coefficient had more effect on RCF life and wear rate of the wheel discs than temperature, for the test scenarios considered.

5. References

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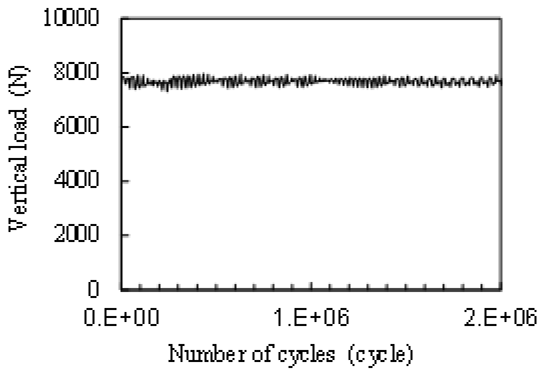
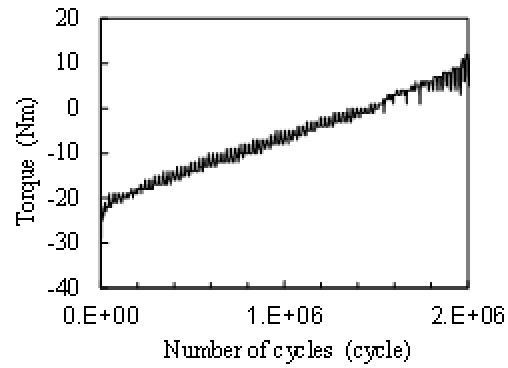
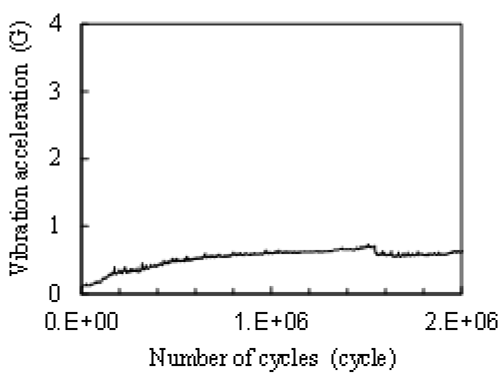
13. Szablewski, D., Cummings, S., and Welander, L. "Effects of Temperature on Wheel Shelling," Technical Report No. DOT/FRA/ORD-20/17, Washington, DC: U.S. Department of Transportation, Federal Railroad Administration, April 2015.

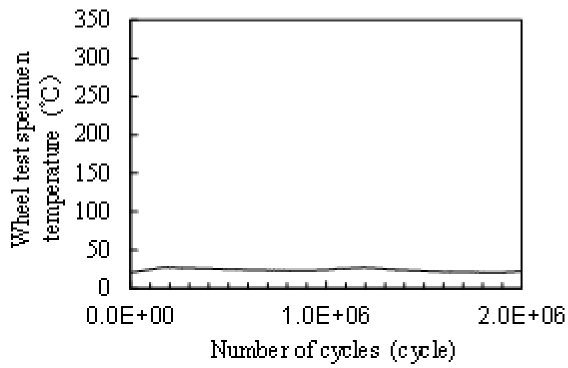
Appendix A.
Test Results for All the Tests

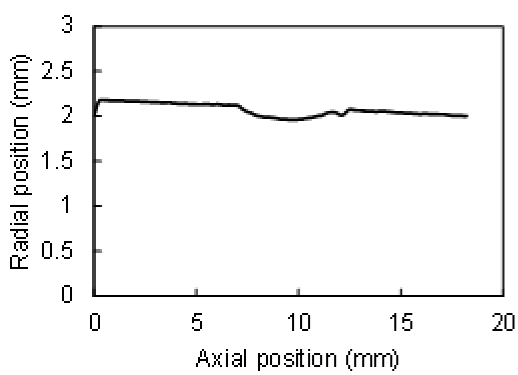
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
17	C1-1-1 (Wheel) 1 (Rail)	Ambient	0.17	5		34.0	36.6
		RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		2,000,000	1,215.3	-0.014	0.019	0.165	Clean

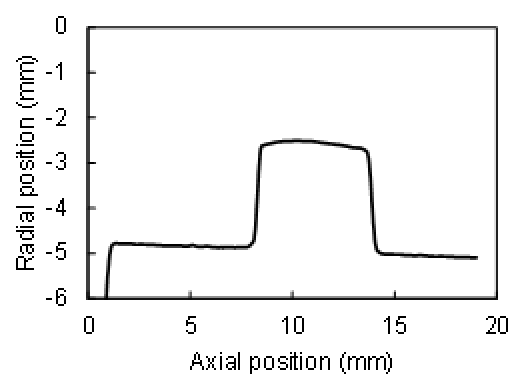


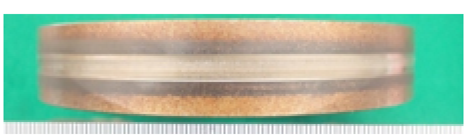




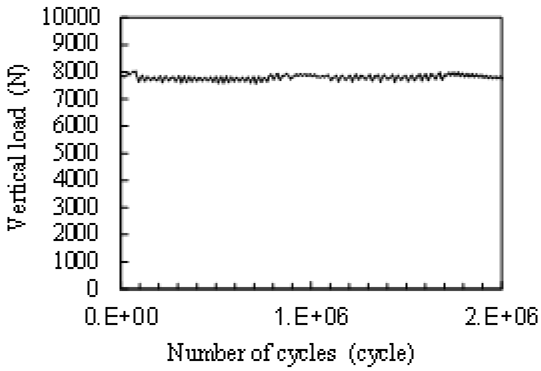


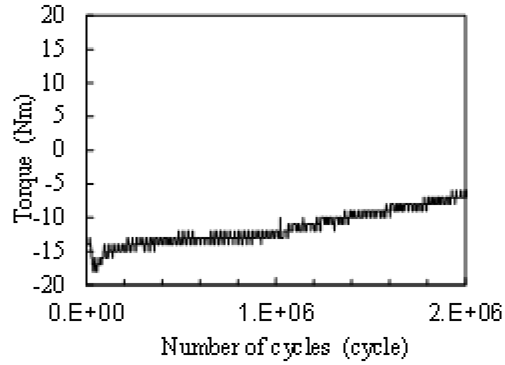


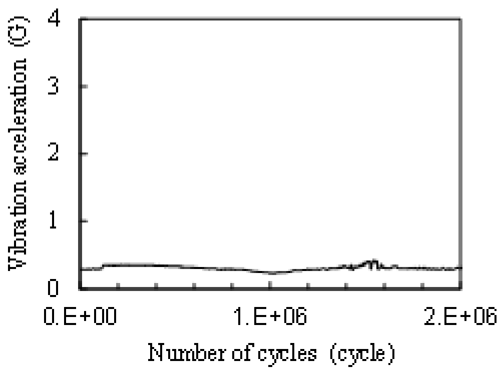


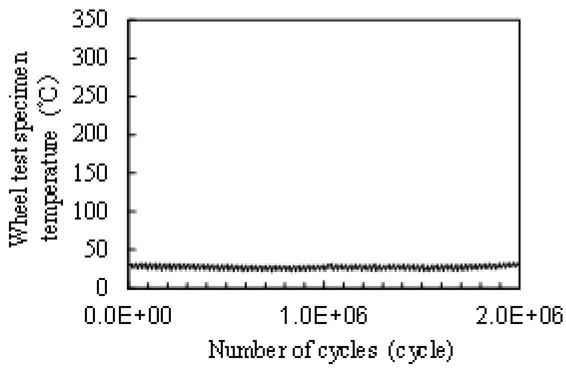


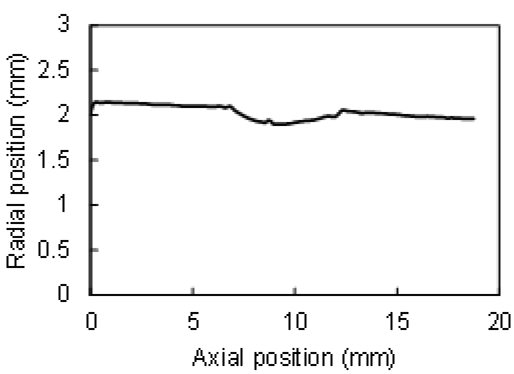
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
		Ambient	0.15	5		31.3	38.3
1	F1-3-1 (Wheel) 41 (Rail)	RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		2,000,000	1,224.0	-0.025	0.025	0.159	Clean

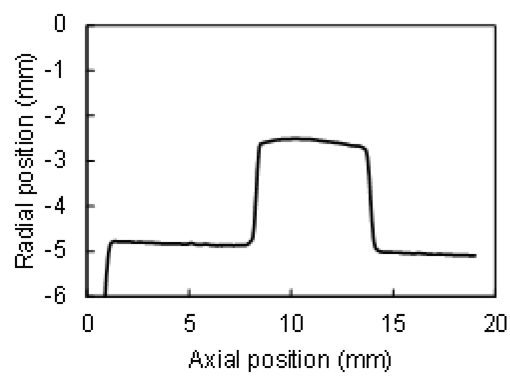


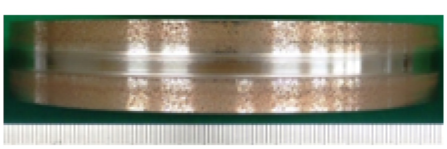


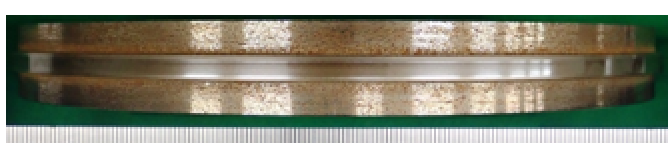




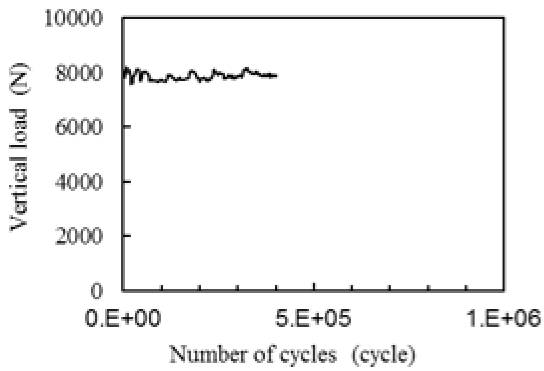


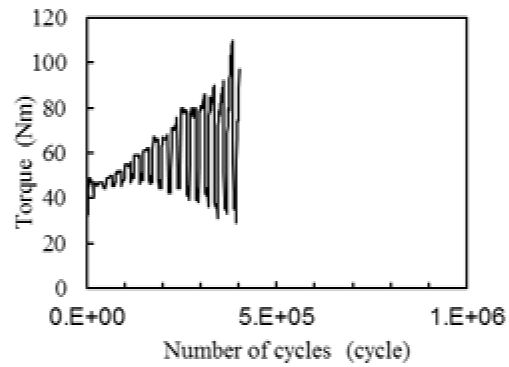


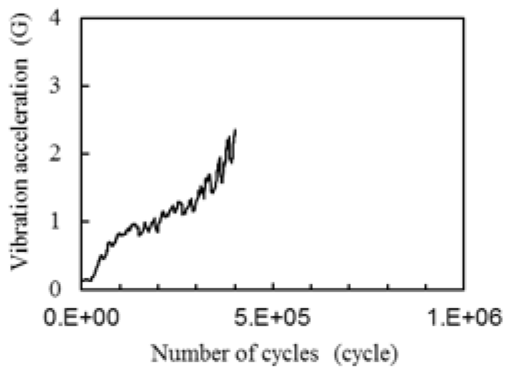


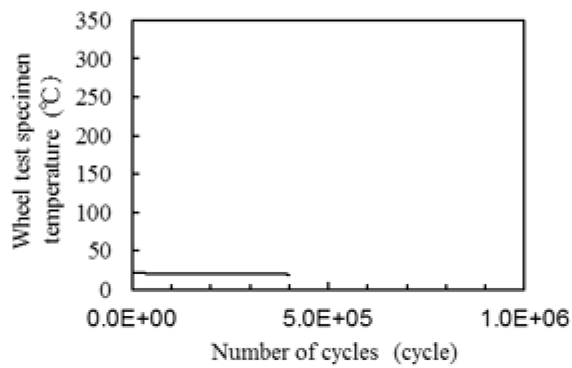


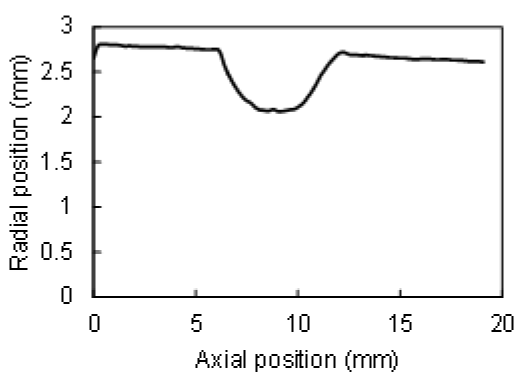
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
5	F1-1-2 (Wheel) 3 (Rail)	Ambient	0.65	5		30.9	38.0
		RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		395,500	1,229.1	0.125	0.125	0.348	Minor shelling

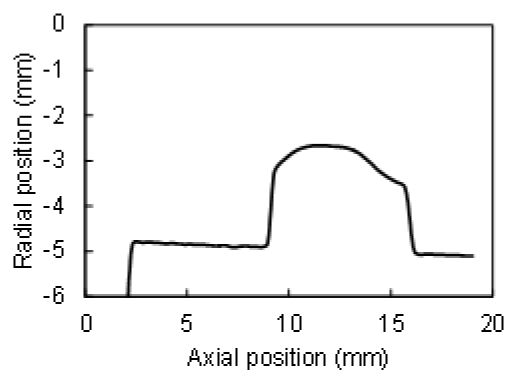


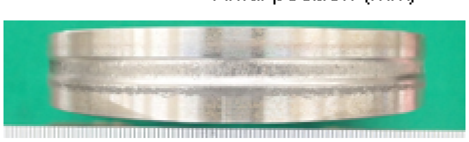


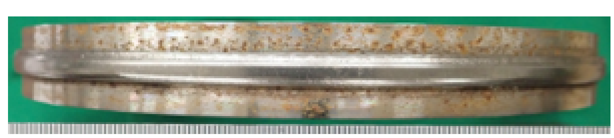




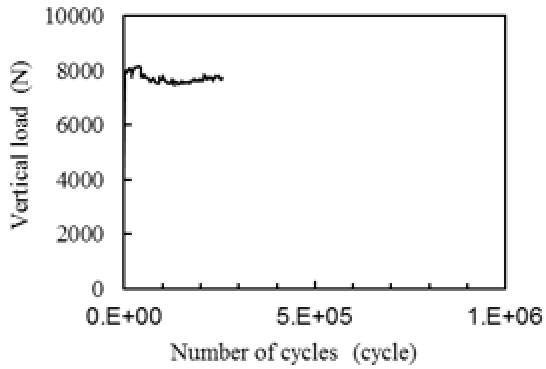


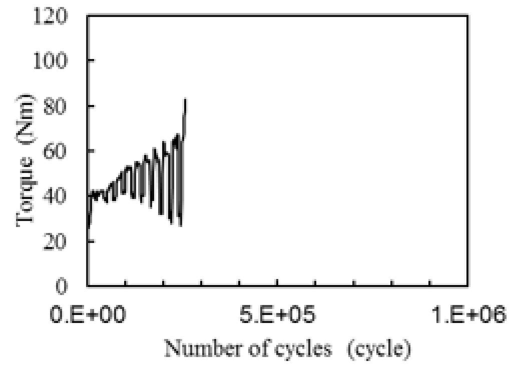


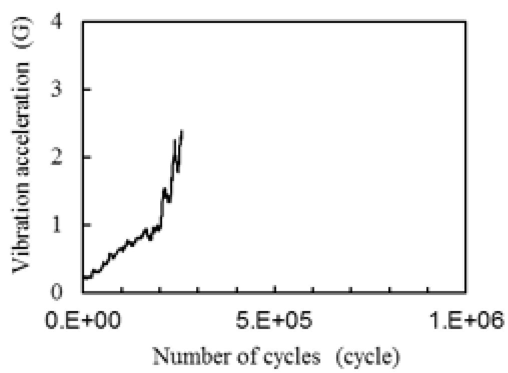


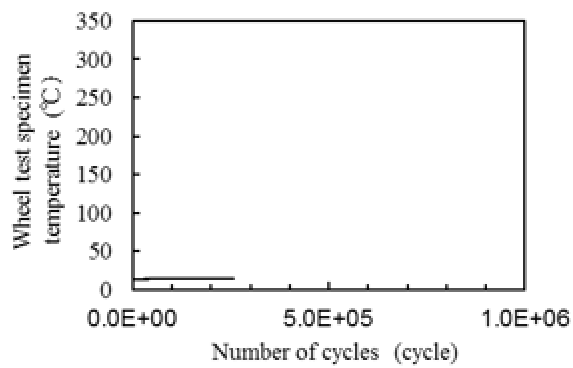


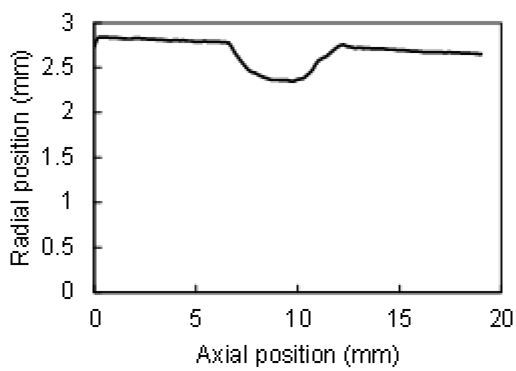
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
21	C1-1-2 (Wheel) 4 (Rail)	Ambient	0.40	5		34.4	37.7
		RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		252,000	1,216.7	0.102	0.102	0.355	Minor shelling

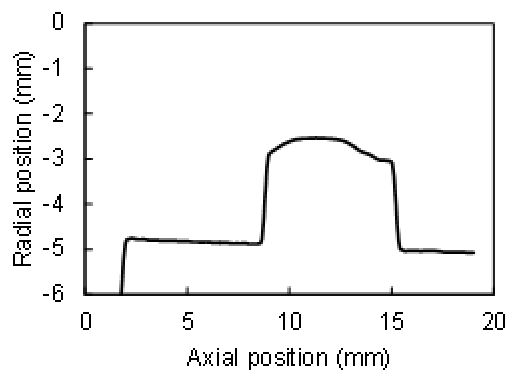


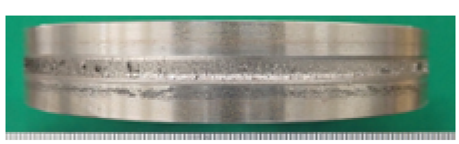


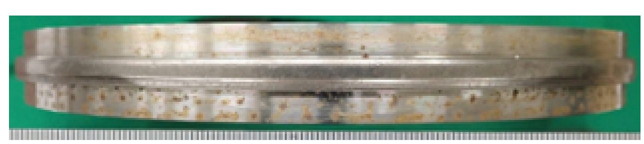




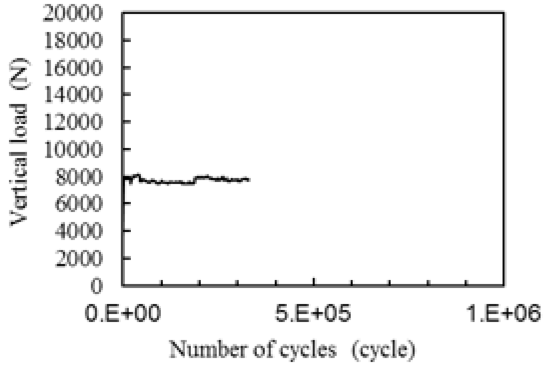


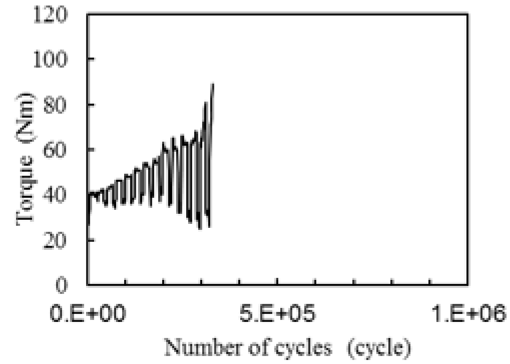


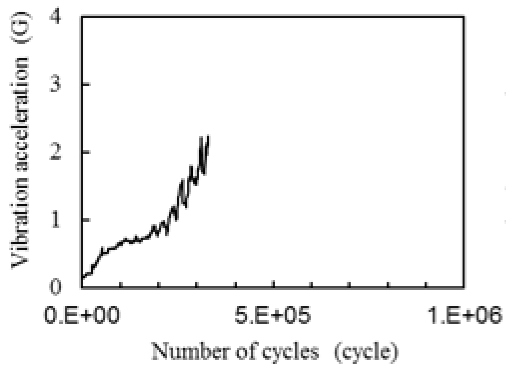


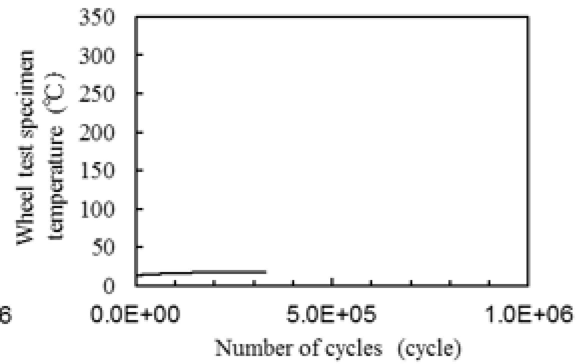


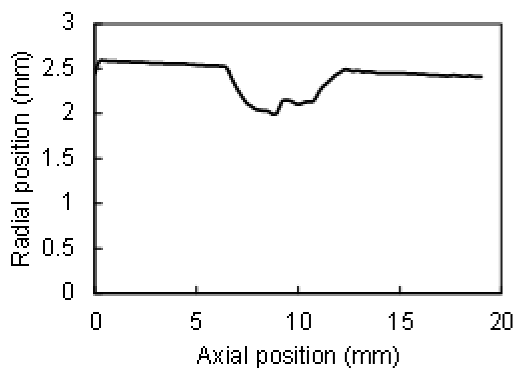
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
		Ambient	0.51	5		34.9	39.0
25	C1-2-1 (Wheel) 5 (Rail)	RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		326,200	1,216.9	0.103	0.103	0.374	Shelling

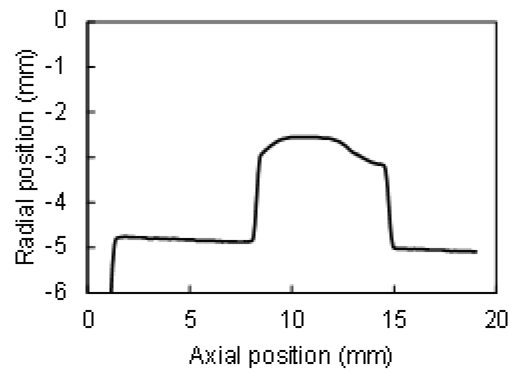


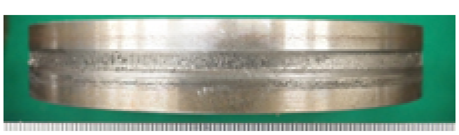


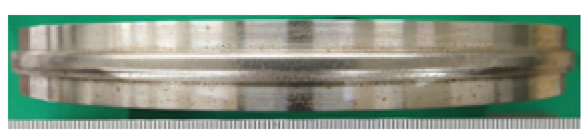




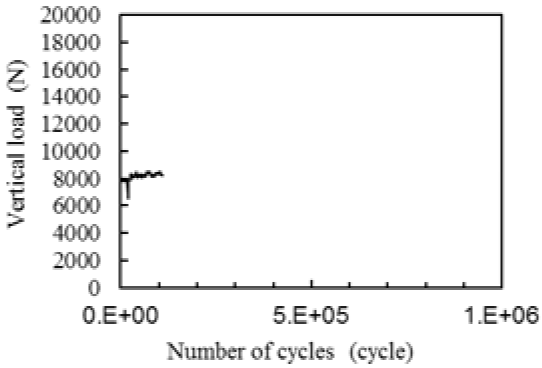


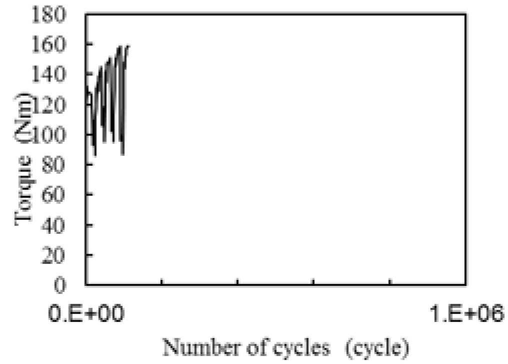


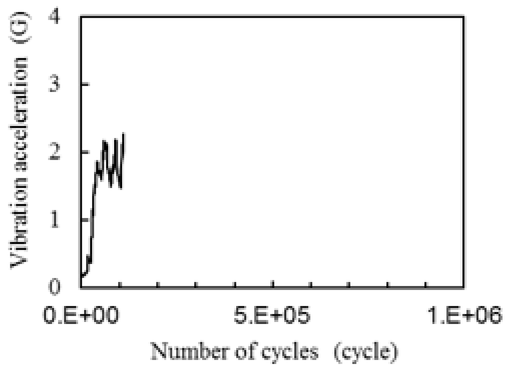


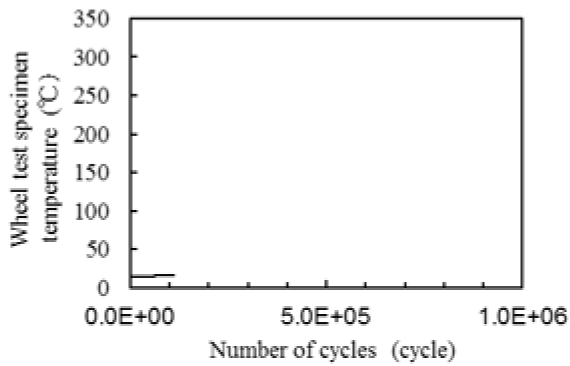


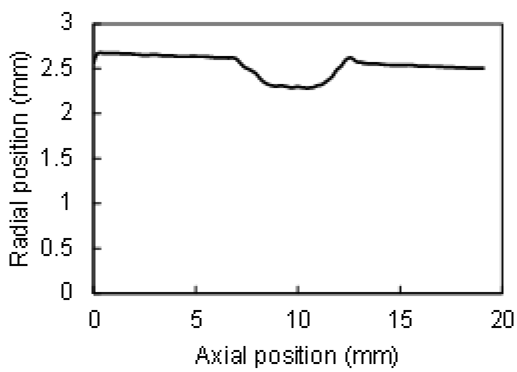
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
		Ambient	0.30	5		31.3	38.5
9	F1-1-3 (Wheel) 6 (Rail)	RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		111,300	1,251.1	0.265	0.265	0.648	Shelling

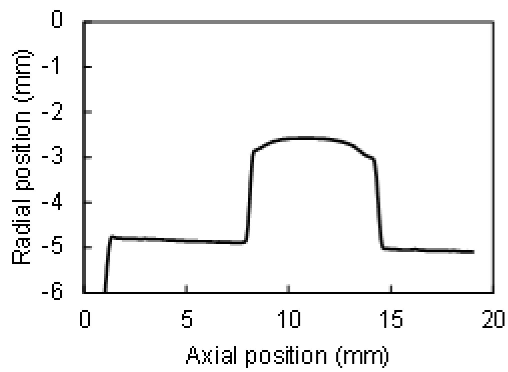


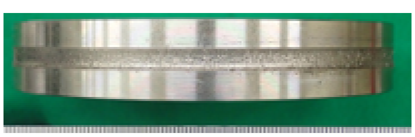


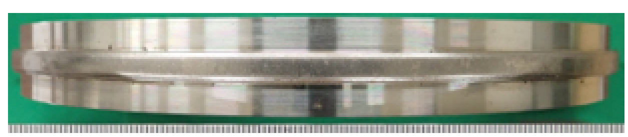




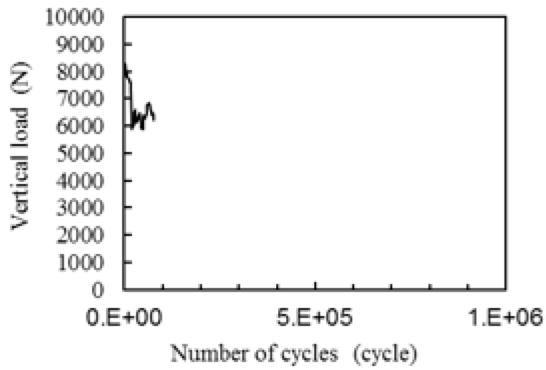


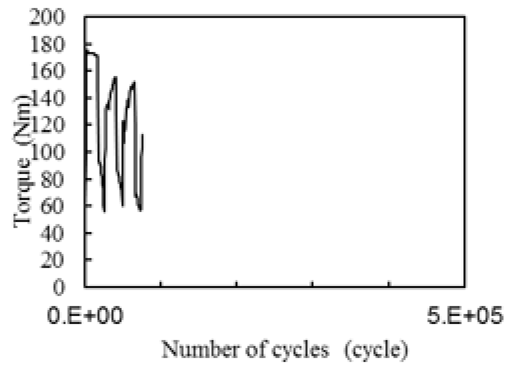


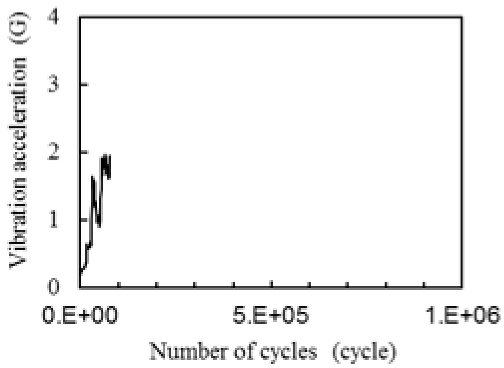


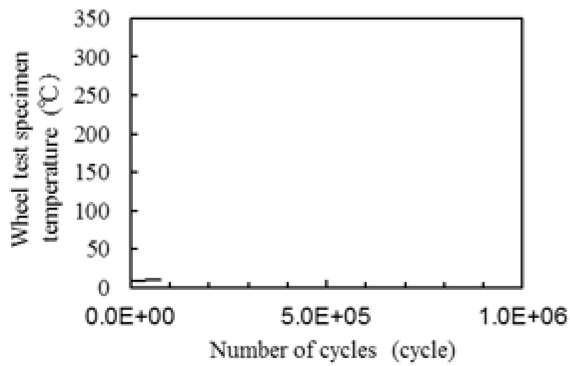


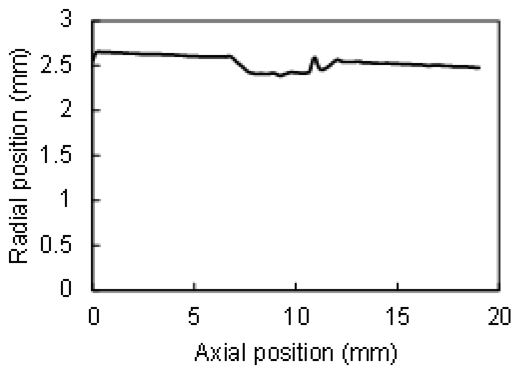
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
29	C1-2-2 (Wheel) 7 (Rail)	Ambient	0.19	5		34.5	39.1
		RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		76,100	1,131.2	0.305	0.305	0.855	Minor shelling

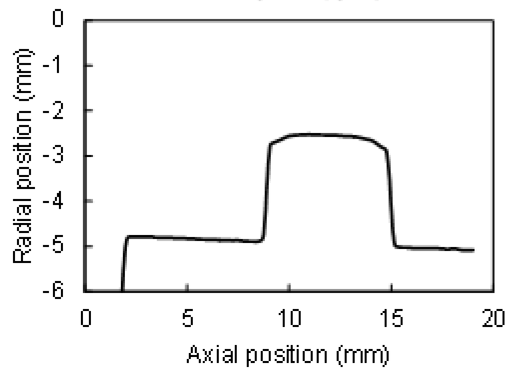


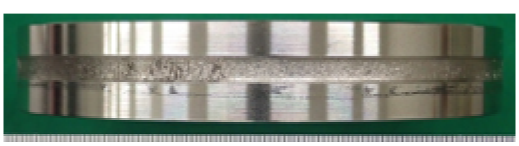


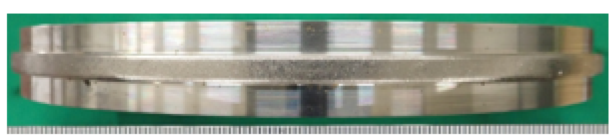




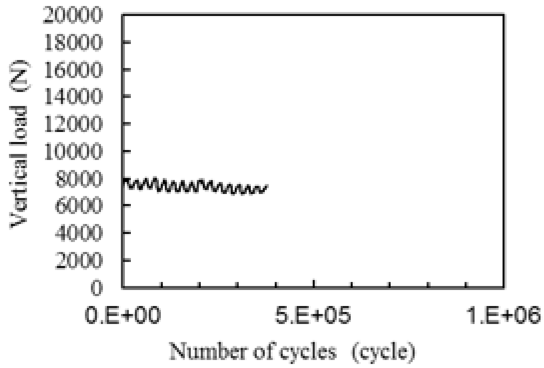


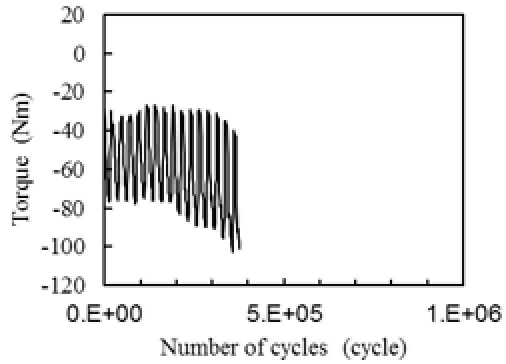


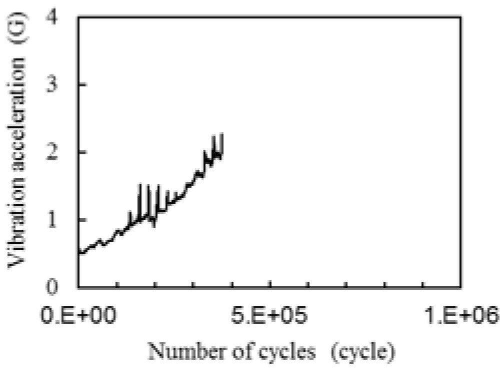


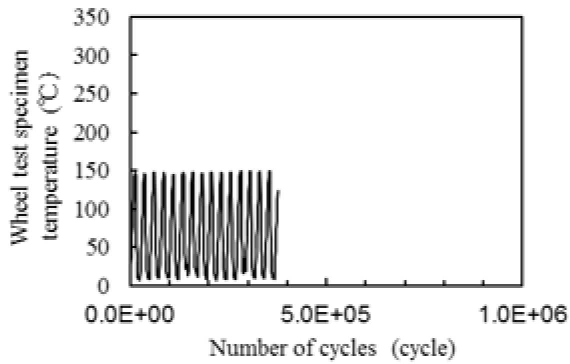


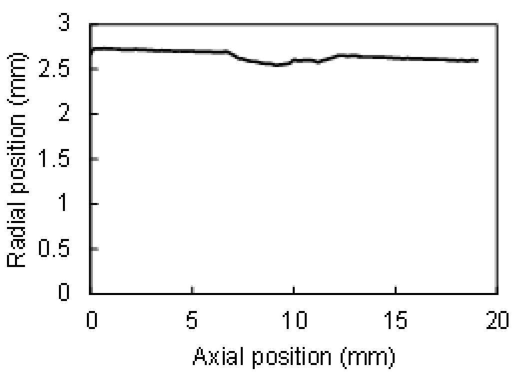
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
		300	0.13	5		34.4	38.9
18	C1-3-1 (Wheel) 9 (Rail)	RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		373,800	1,190.4	-0.135	0.135	0.137	Minor shelling

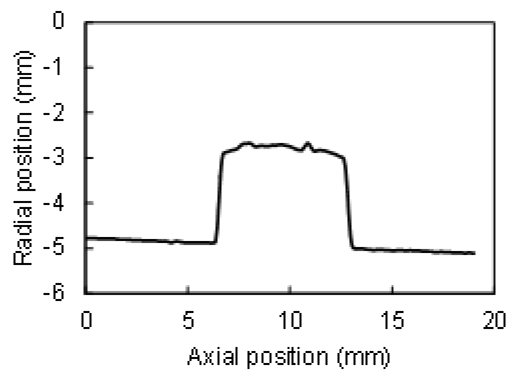


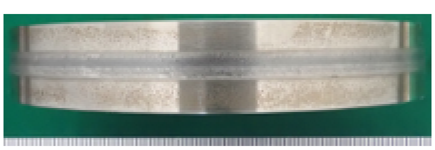


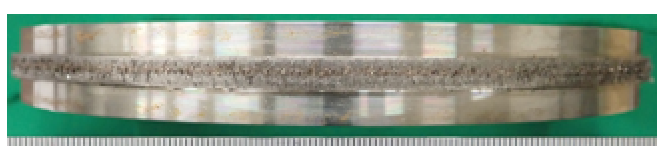












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<tr><td>Wheel</td><td>Rail</td></tr>
<tr><td>300</td><td>0.18</td><td colspan="2">5</td><td>31.9</td><td>38.1</td></tr>
<tr><td rowspan="3">2</td><td rowspan="3">F1-2-2 (Wheel) 10 (Rail)</td><td rowspan="2">RCF life [cycle]</td><td rowspan="2">Hertzian stress [MPa]</td><td colspan="2">Traction coefficient</td><td rowspan="2">Slip ratio [%]</td><td rowspan="2">Surface condition</td></tr>
<tr><td>Average</td><td>Average of absolute</td></tr>
<tr><td>788,900</td><td>1,192.7</td><td>-0.107</td><td>0.107</td><td>0.145</td><td>Minor shelling</td></tr>
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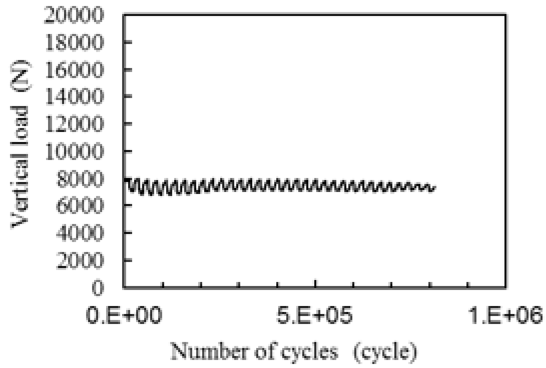
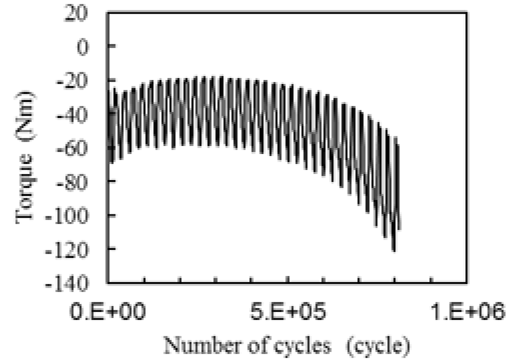
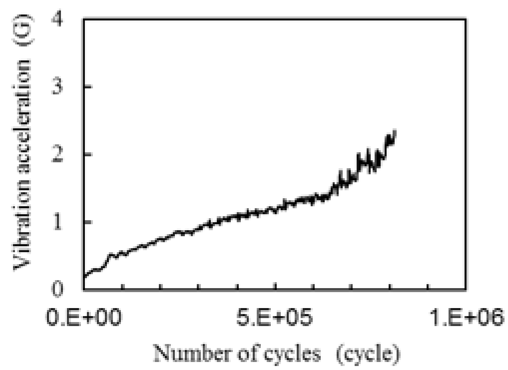
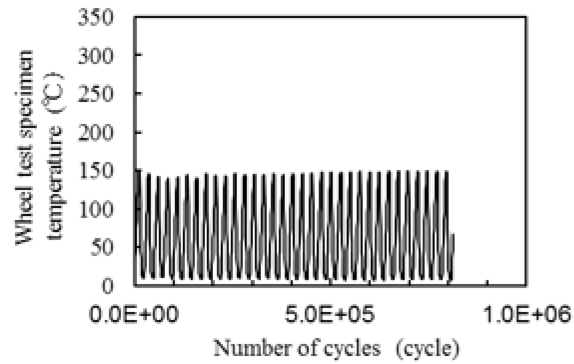
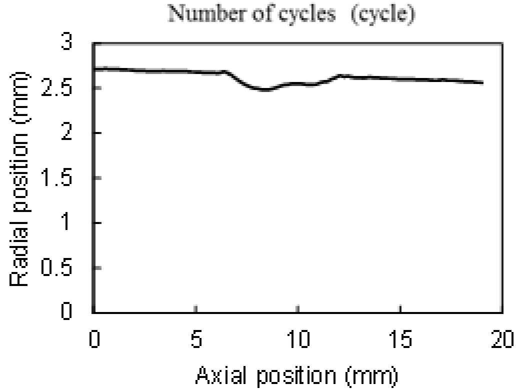
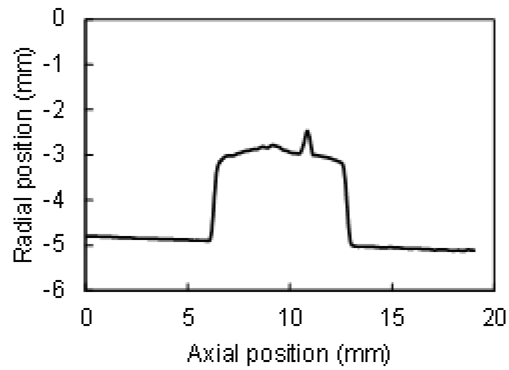


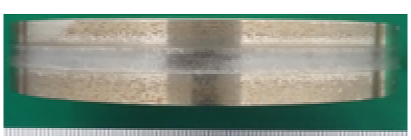




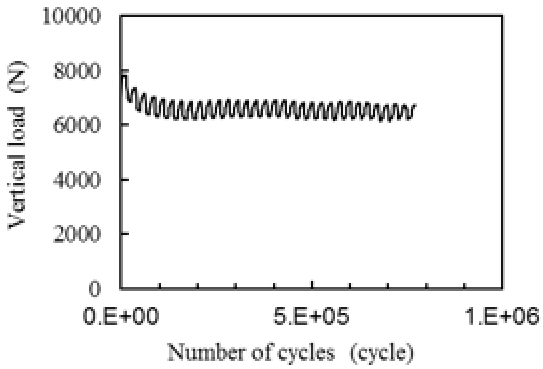


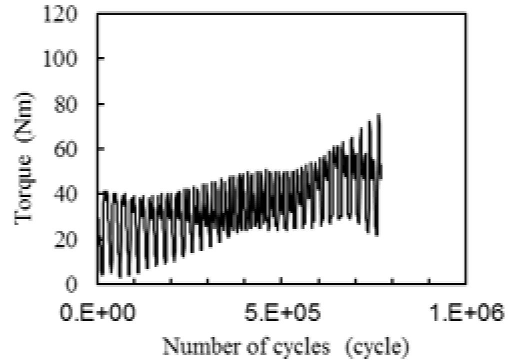


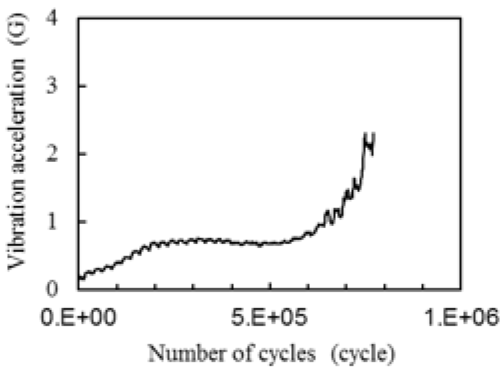


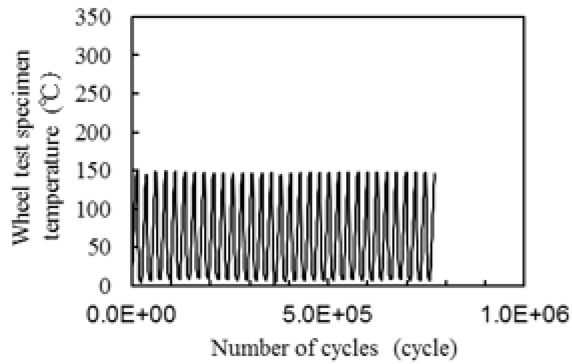


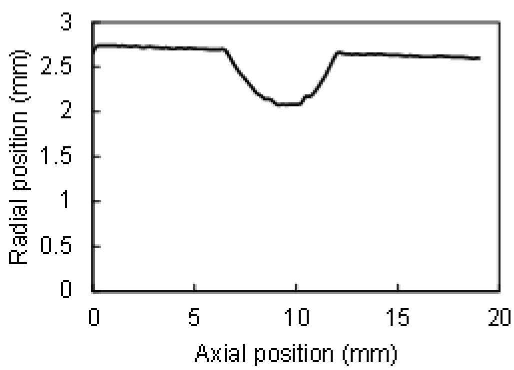
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
		300	0.60	5		35.8	38.1
22	C2-1-1 (Wheel) 11 (Rail)	RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		769,300	1,124.9	0.086	0.086	0.369	Shelling

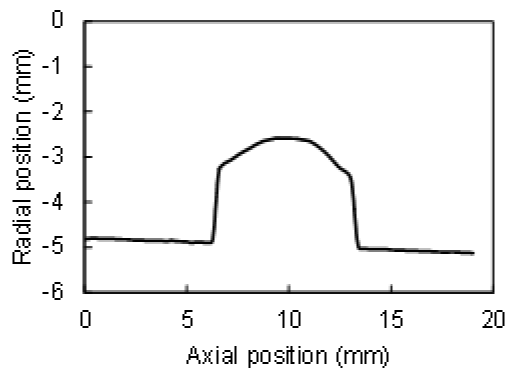


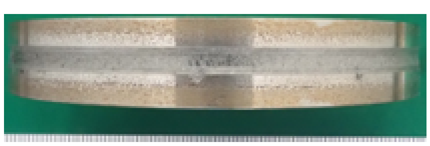


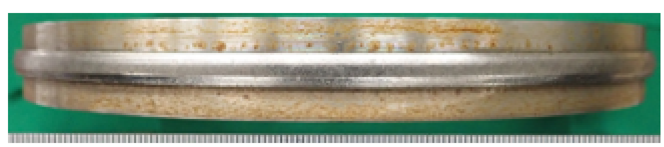




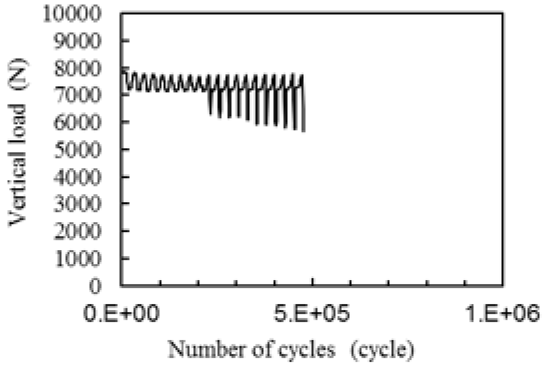


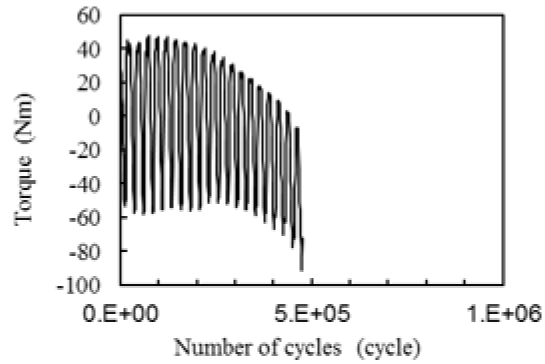


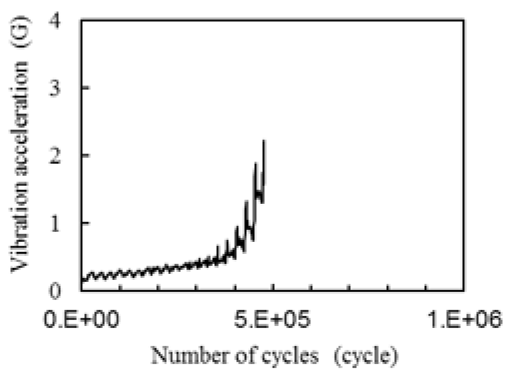


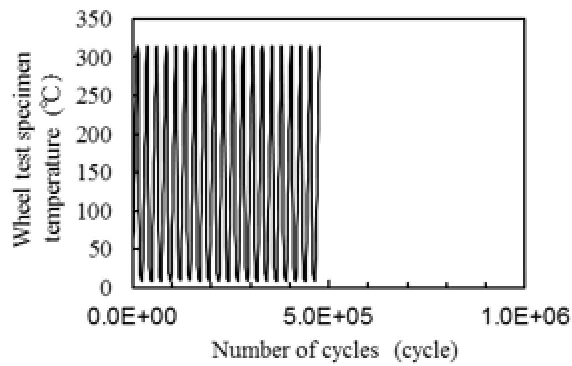


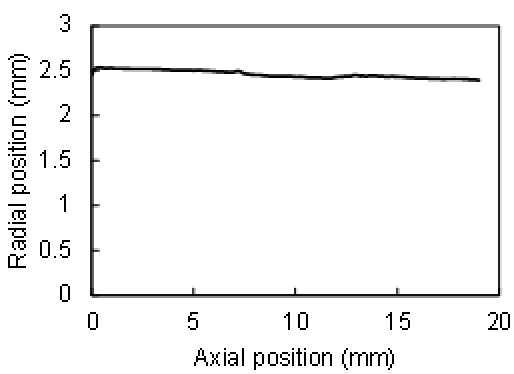
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
23	C2-4-1 (Wheel) 14 (Rail)	600	0.08	5		35.1	39.1
		RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		476,700	1,182.5	-0.012	0.075	0.369	Clean

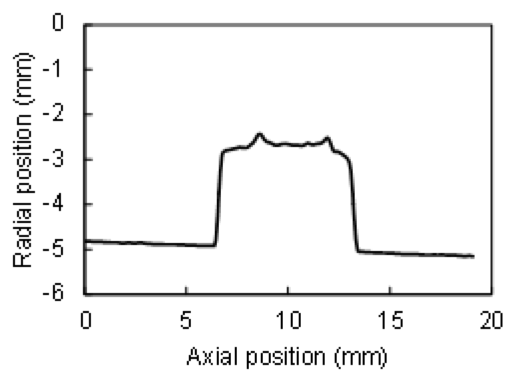


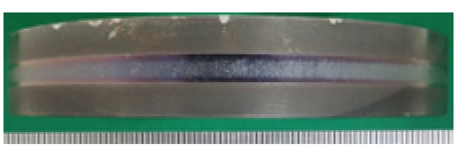


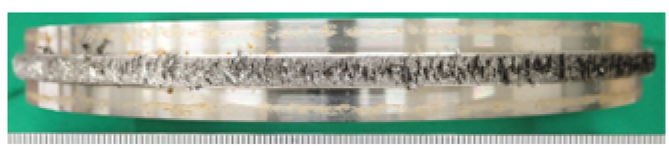




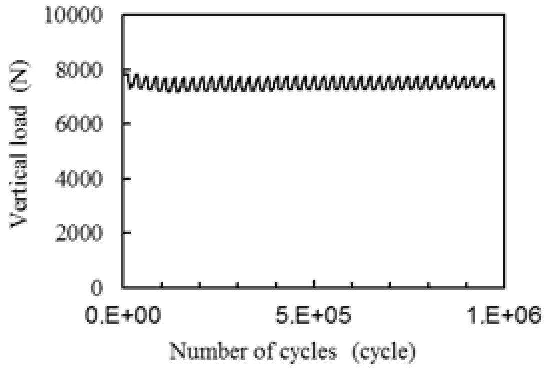


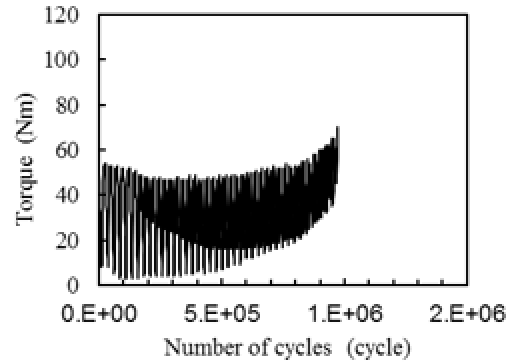


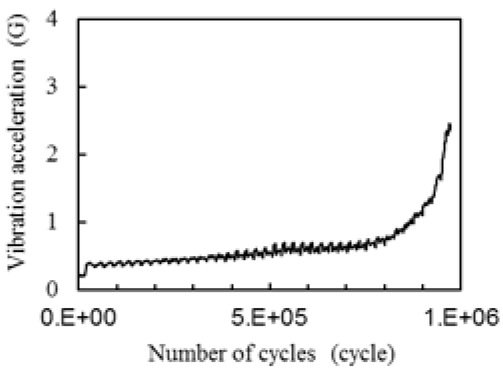


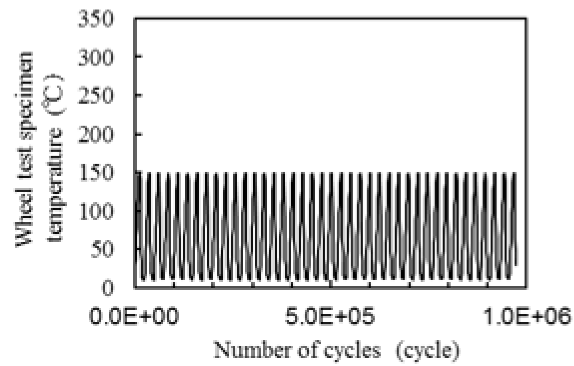


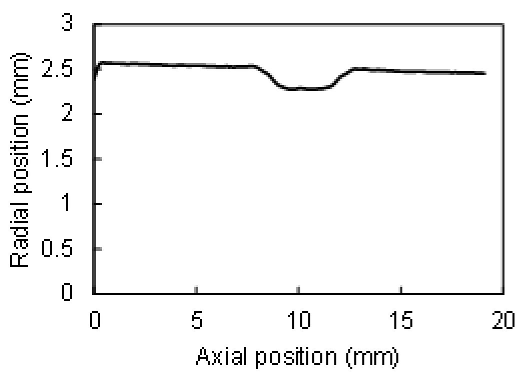
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
6	F2-1-1 (Wheel) 15 (Rail)	300	0.27	5		32.0	39.1
		RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		955,500	1,197.1	0.069	0.069	0.370	Shelling

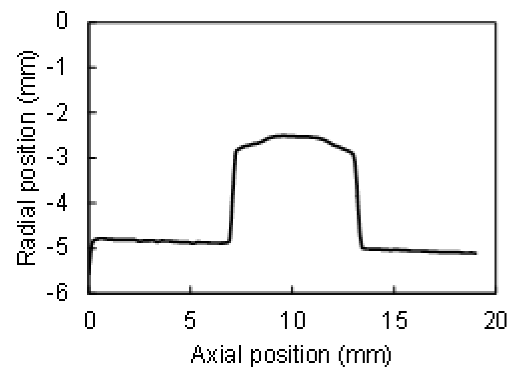


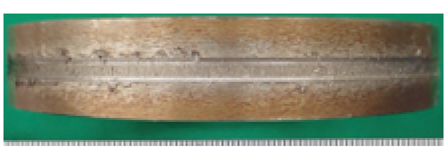


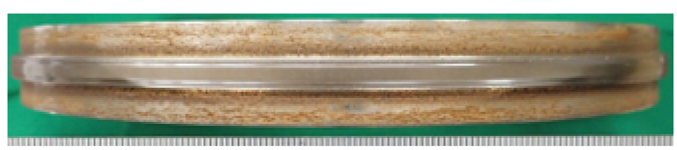




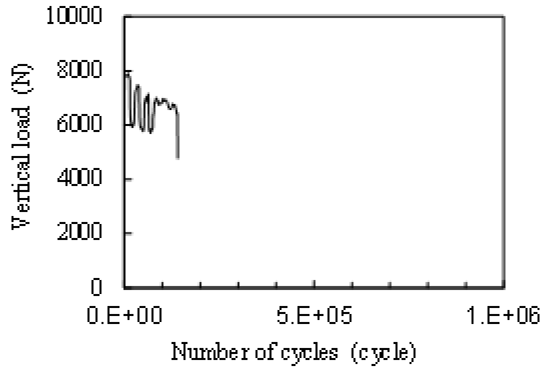


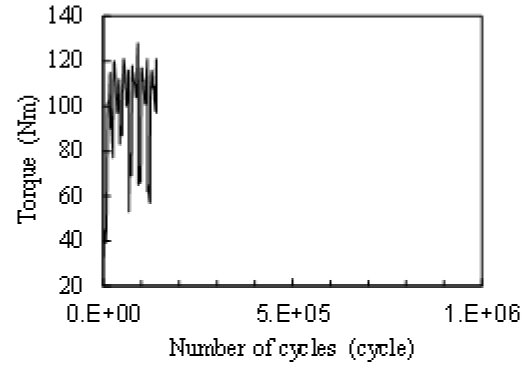


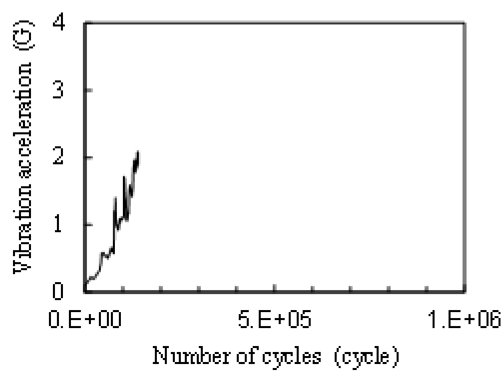


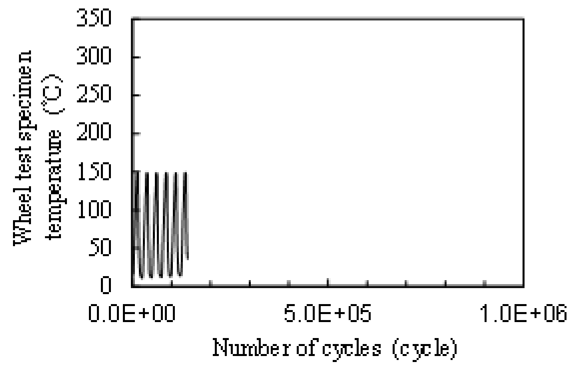


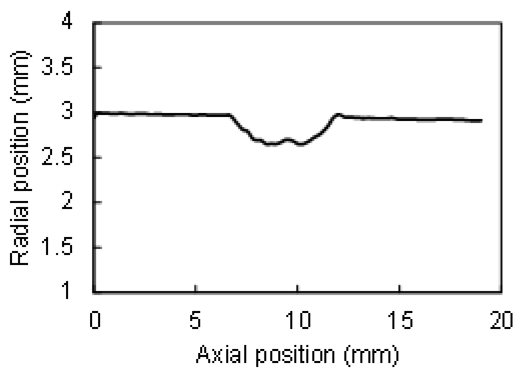
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
26	C2-4-2 (Wheel) 16 (Rail)	300	0.31	5		35.8	39.1
		RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		140,000	1,136.3	0.238	0.238	0.627	Minor shelling

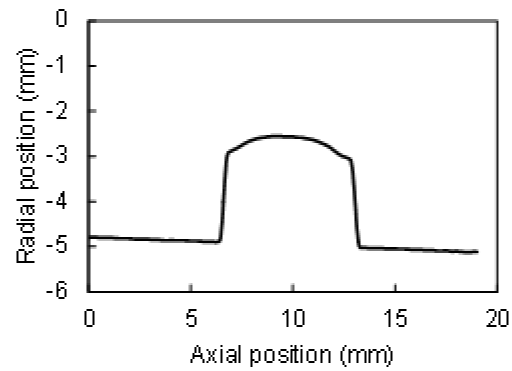


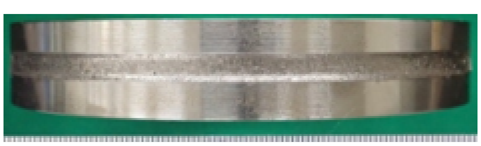


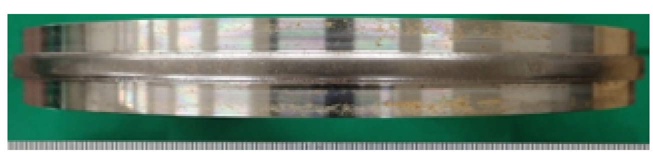




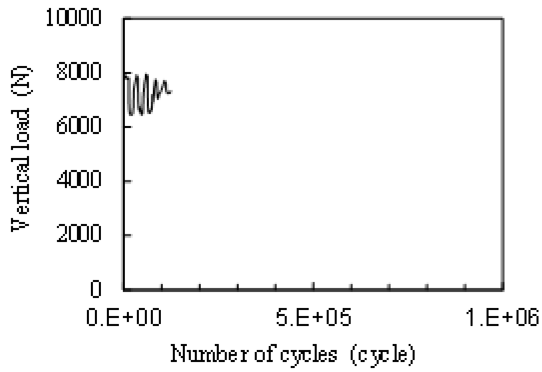


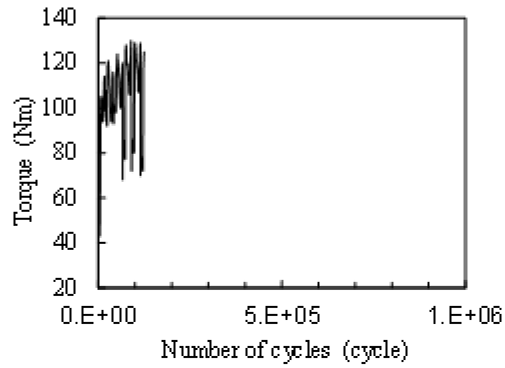


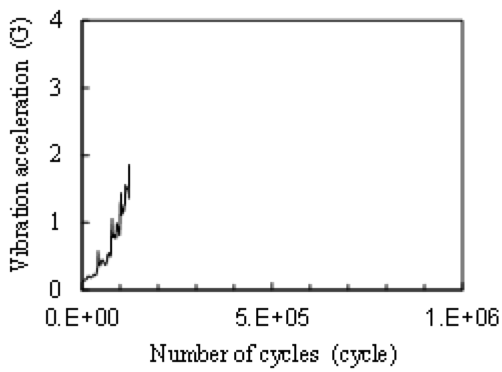


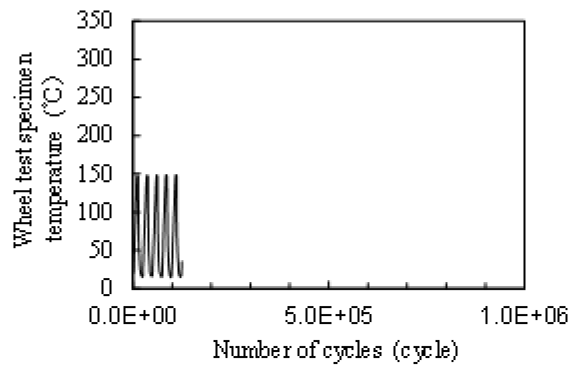


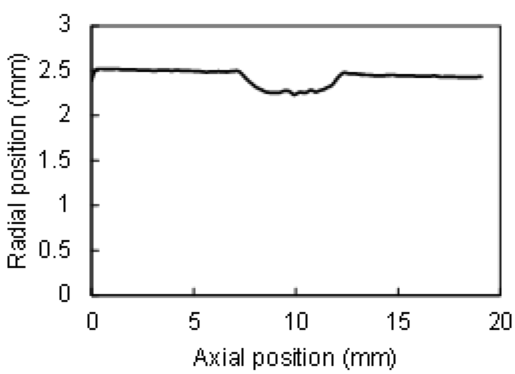
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
10	F2-1-2 (Wheel) 17 (Rail)	300	0.24	5		32.0	39.4
		RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		124,600	1,180.3	0.235	0.235	0.628	Minor shelling

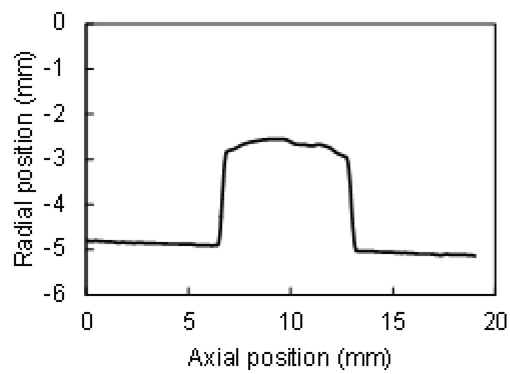


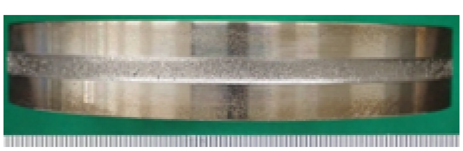


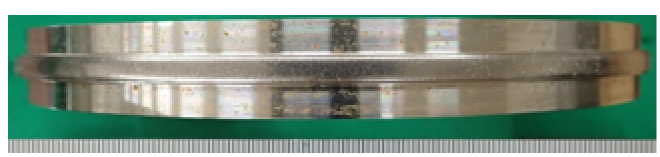












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<tr><td>Wheel</td><td>Rail</td></tr>
<tr><td>300</td><td>0.44</td><td colspan="2">5</td><td>35.9</td><td>38.1</td></tr>
<tr><td rowspan="3">30</td><td rowspan="3">C3-1-1 (Wheel) 18 (Rail)</td><td rowspan="2">RCF life [cycle]</td><td rowspan="2">Hertzian stress [MPa]</td><td colspan="2">Traction coefficient</td><td rowspan="2">Slip ratio [%]</td><td rowspan="2">Surface condition</td></tr>
<tr><td>Average</td><td>Average of absolute</td></tr>
<tr><td>76,300</td><td>1,165.7</td><td>0.296</td><td>0.296</td><td>0.855</td><td>Minor shelling</td></tr>
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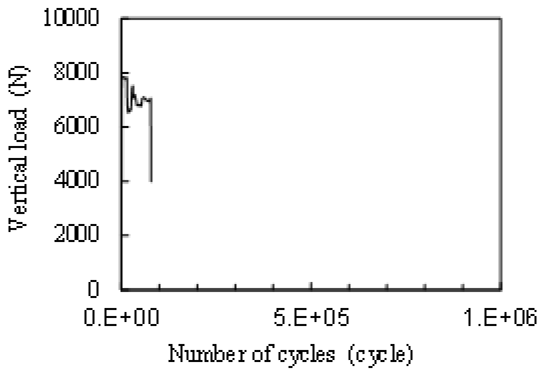
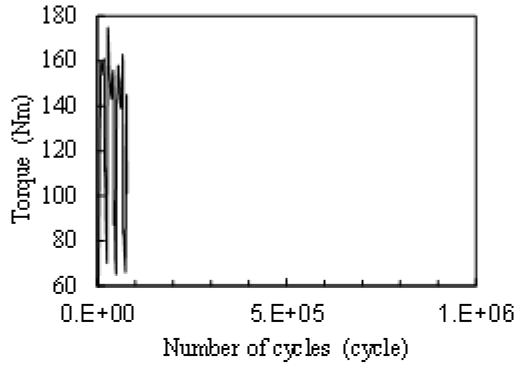
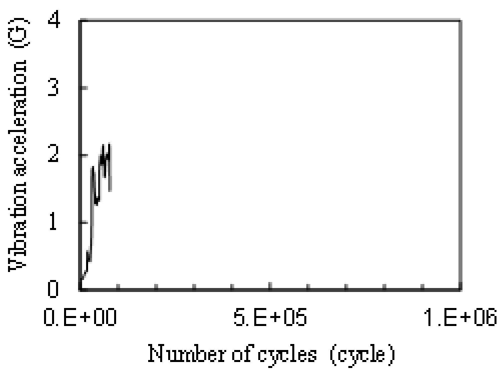
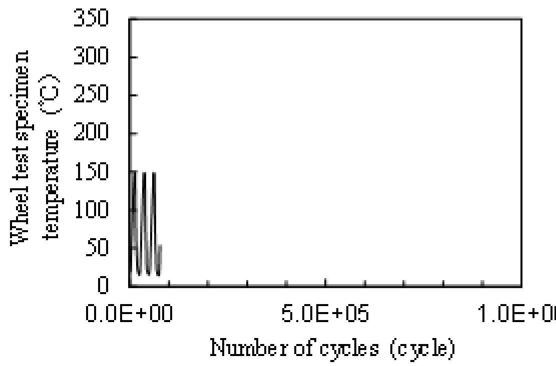
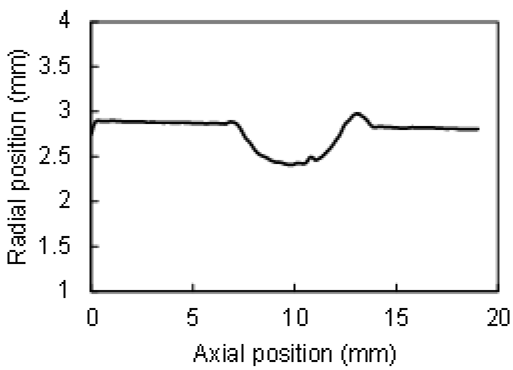
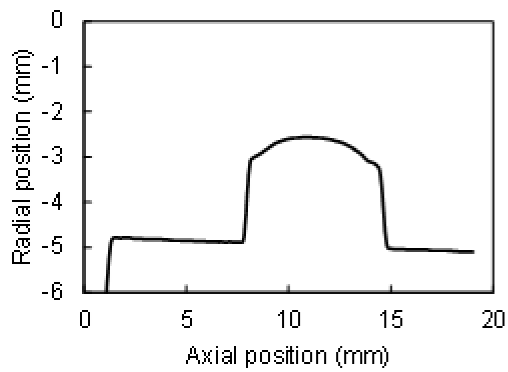


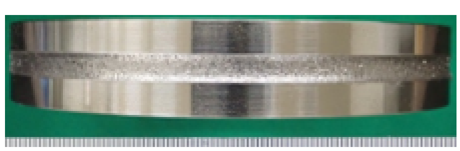


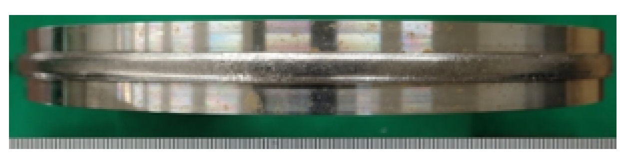




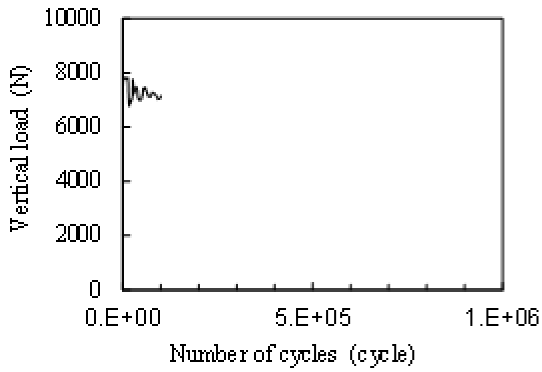


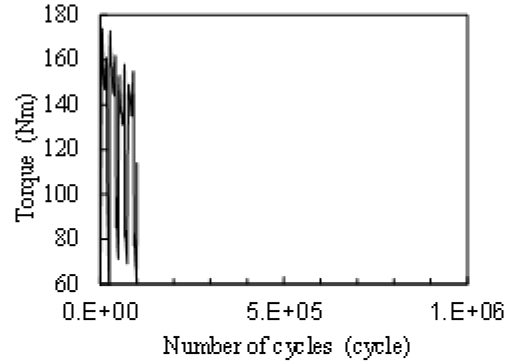


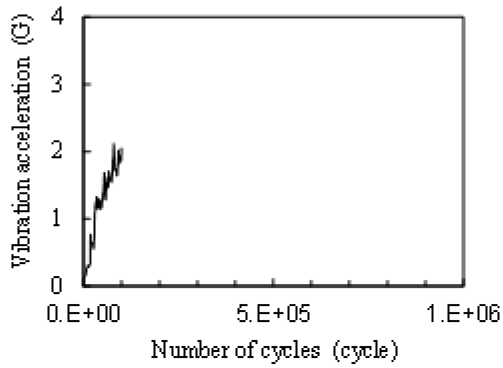


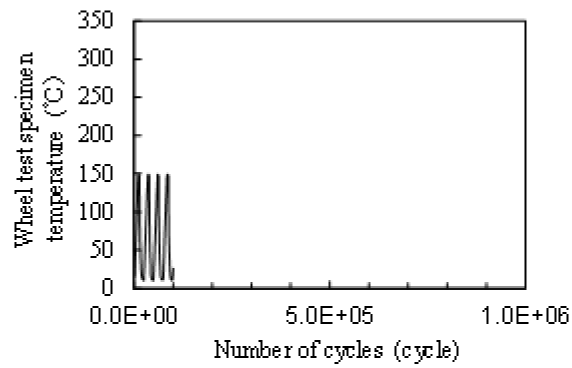


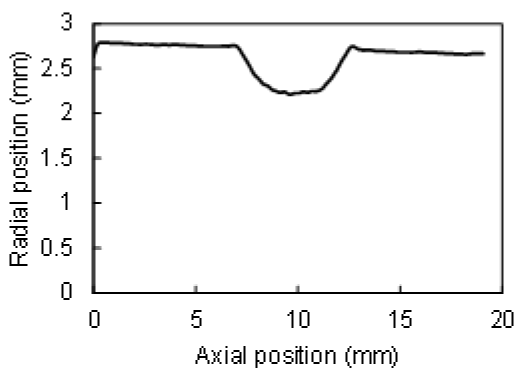
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
		300	0.51	5		32.1	38.1
14	F2-1-3 (Wheel) 19 (Rail)	RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		100,100	1,182.1	0.287	0.287	0.887	Minor shelling

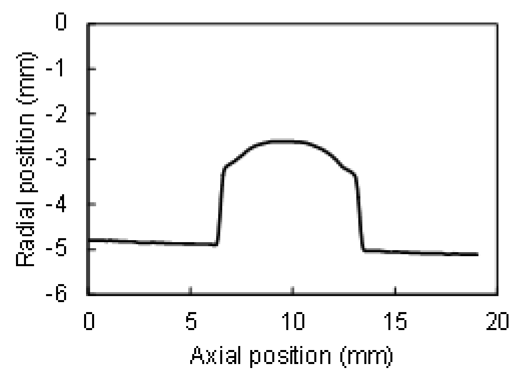


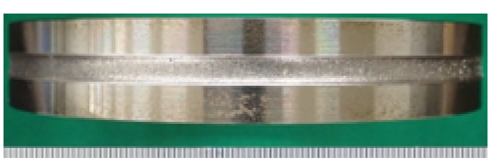
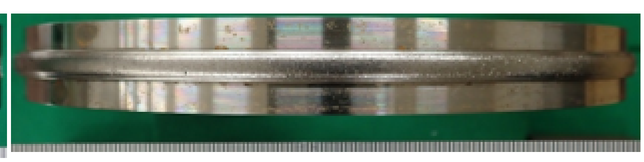










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<tr><td>Wheel</td><td>Rail</td></tr>
<tr><td>600</td><td>0.15</td><td colspan="2">5</td><td>35.7</td><td>37.8</td></tr>
<tr><td rowspan="3">19</td><td rowspan="3">C3-1-2 (Wheel) 20 (Rail)</td><td rowspan="2">RCF life [cycle]</td><td rowspan="2">Hertzian stress [MPa]</td><td colspan="2">Traction coefficient</td><td rowspan="2">Slip ratio [%]</td><td rowspan="2">Surface condition</td></tr>
<tr><td>Average</td><td>Average of absolute</td></tr>
<tr><td>262,500</td><td>1,219.3</td><td>-0.168</td><td>0.168</td><td>0.123</td><td>Clean</td></tr>
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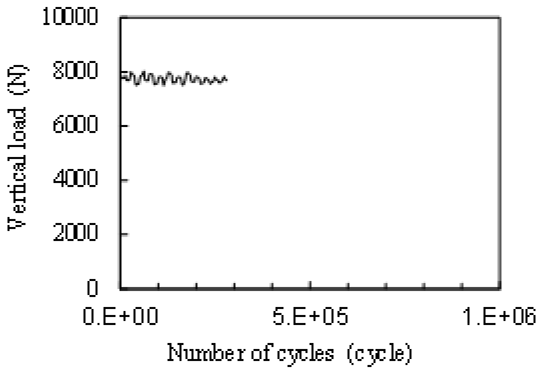
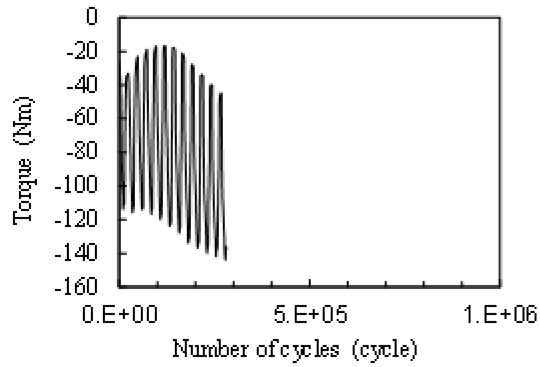
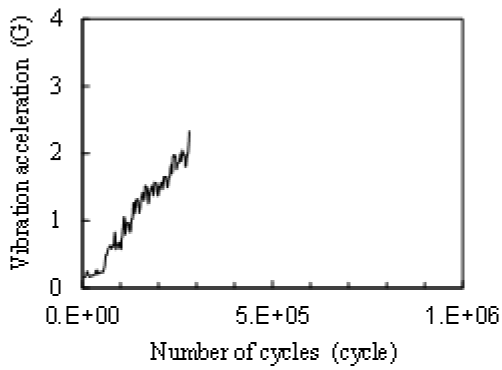
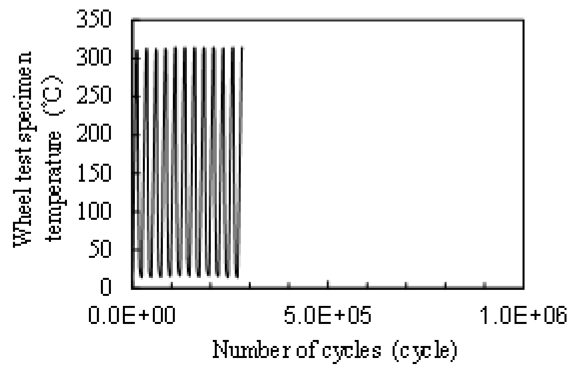
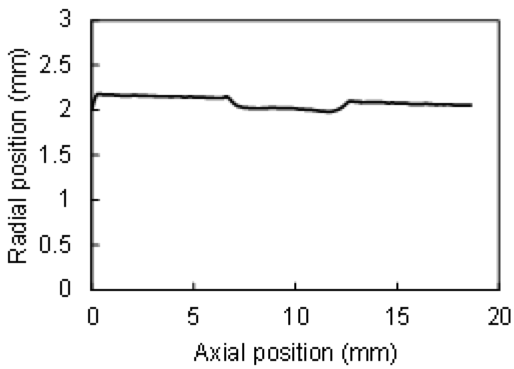
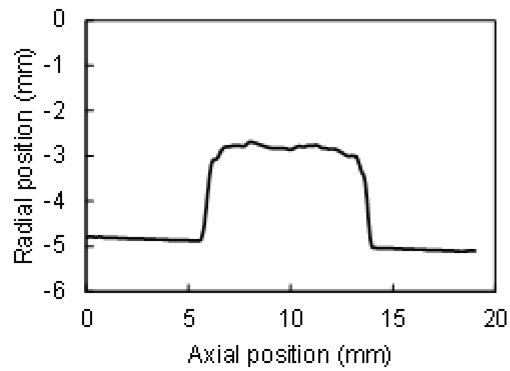


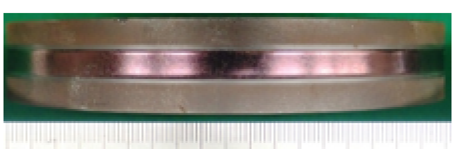


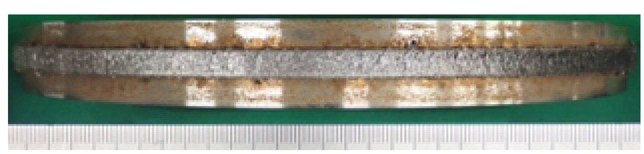




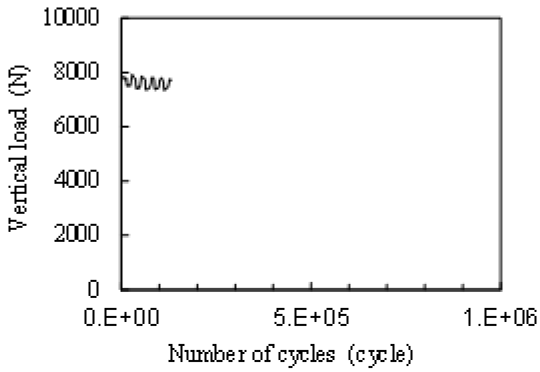


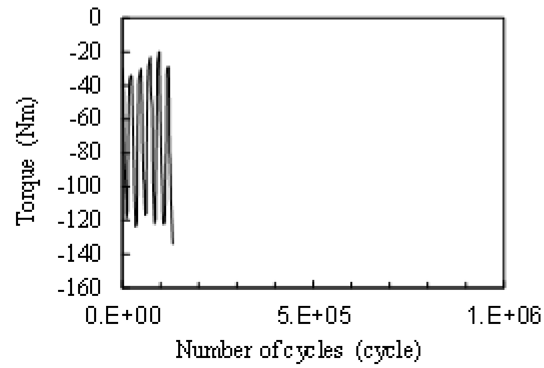


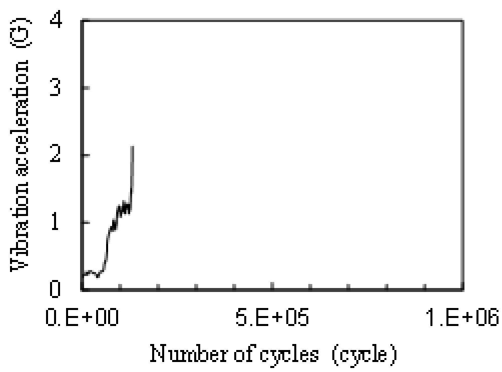


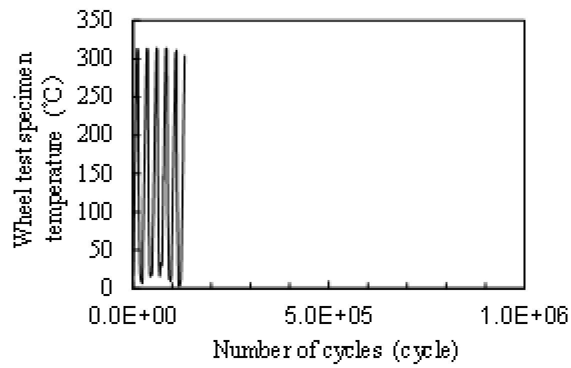


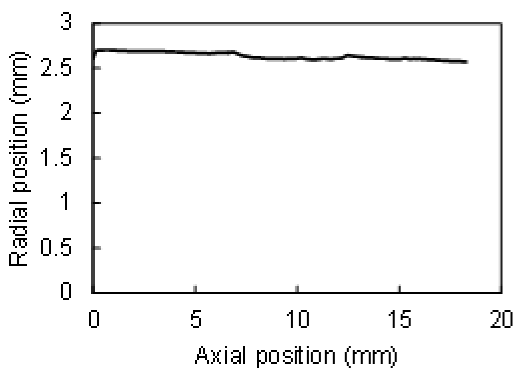
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
		600	0.10	5		32.6	37.8
3	F2-2-1 (Wheel) 21 (Rail)	RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		132,300	1,209.9	-0.158	0.158	0.131	Clean

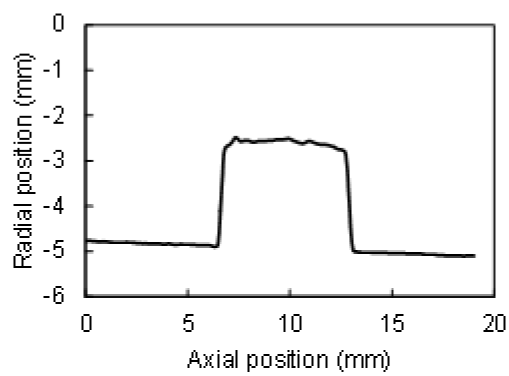


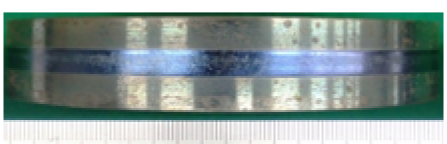


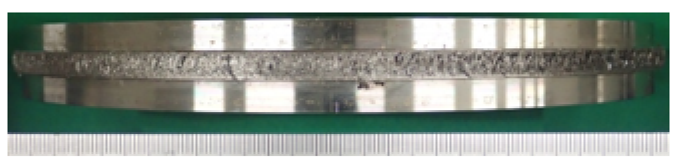




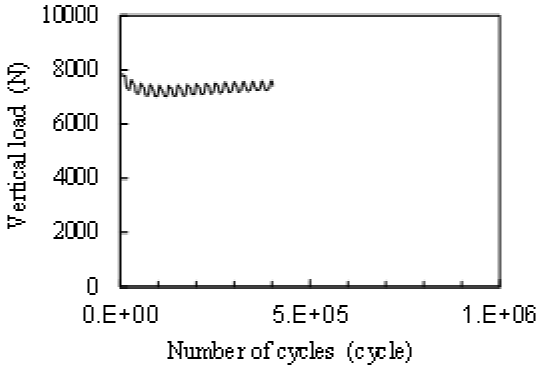


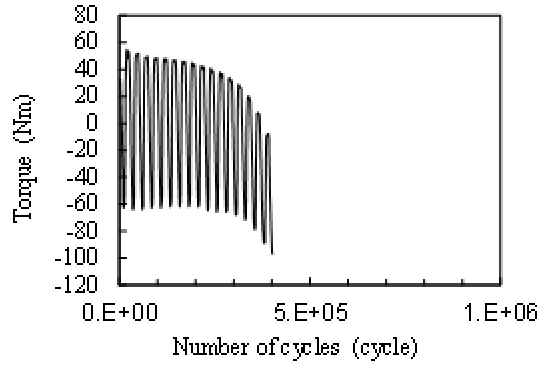


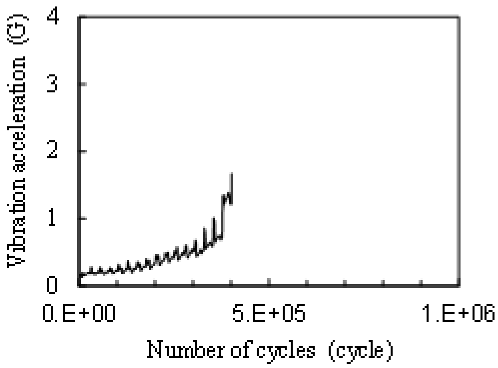


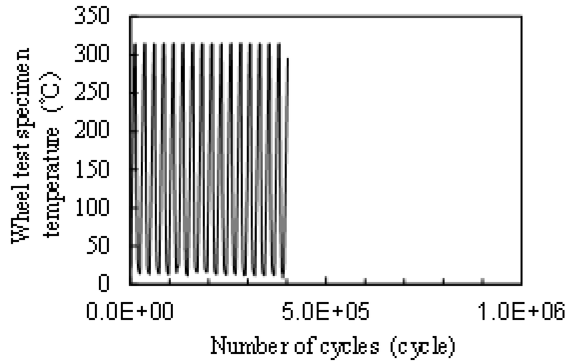


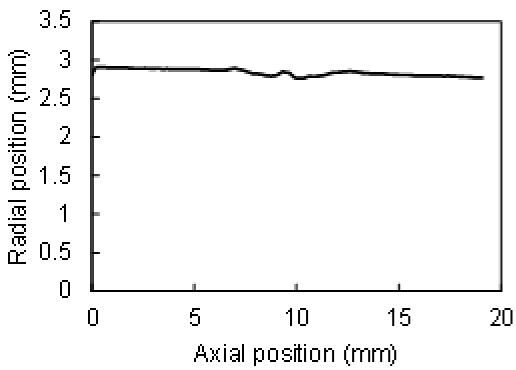
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
7	F2-2-2 (Wheel) 22 (Rail)	600	0.10	5		32.4	40.0
		RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		401,800	1,185.8	-0.009	0.087	0.359	Shelling

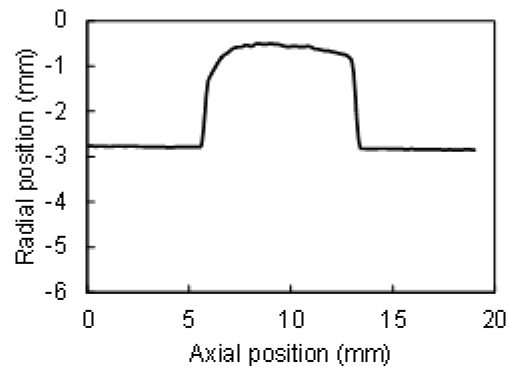


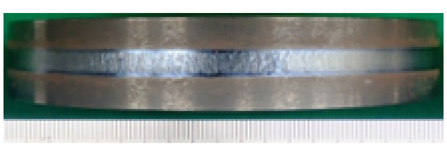




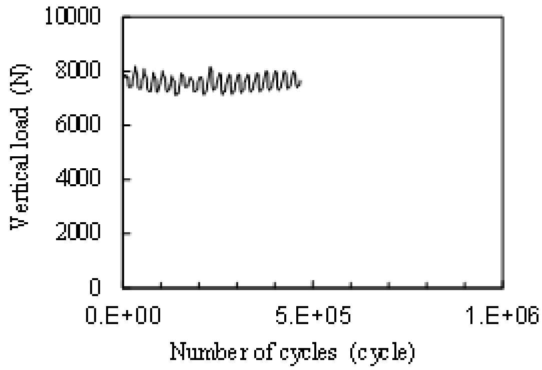


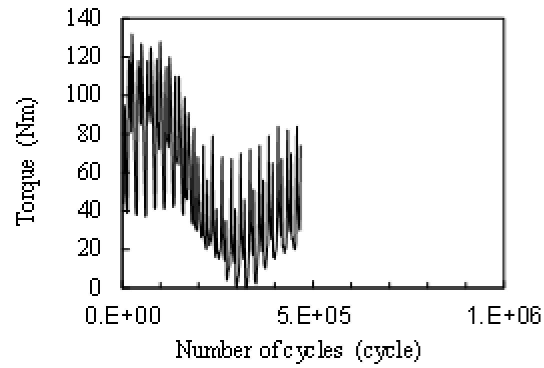


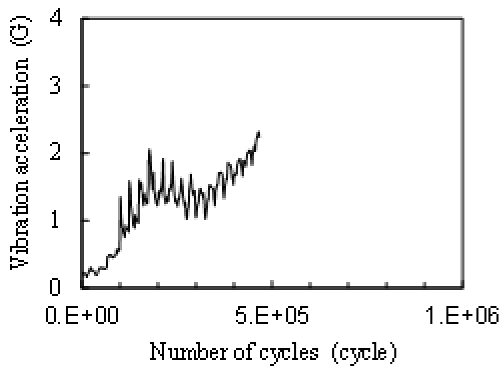


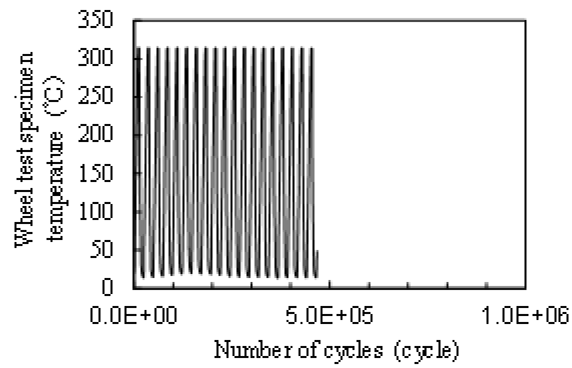


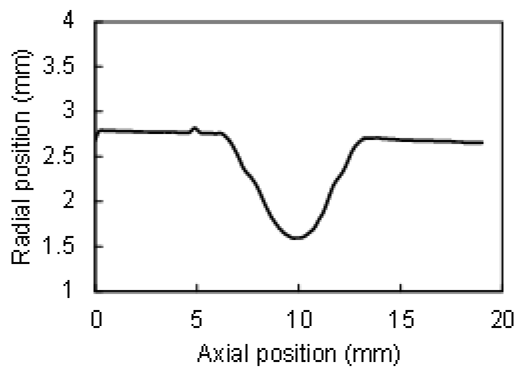
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
		600	1.16	5		34.7	40.8
27	C3-2-1 (Wheel) 23 (Rail)	RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		435,400	1,206.8	0.108	0.108	0.628	Minor shelling

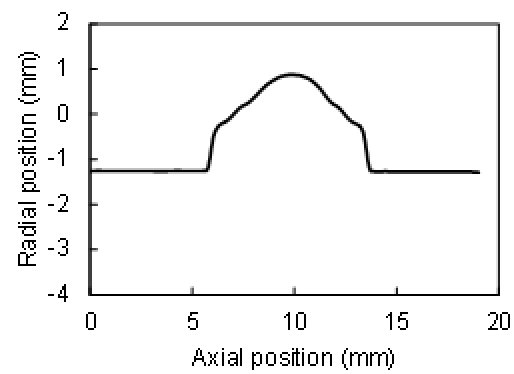


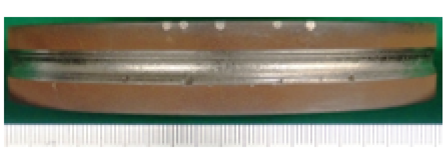


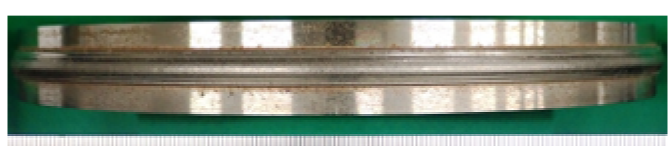




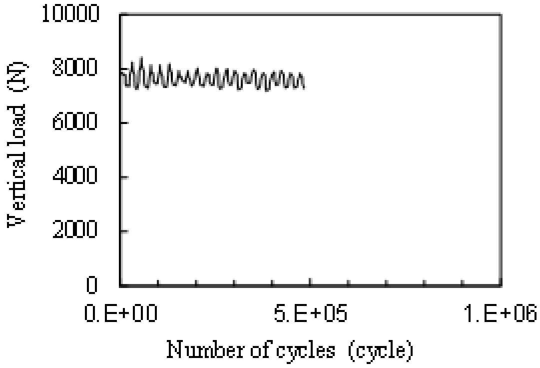


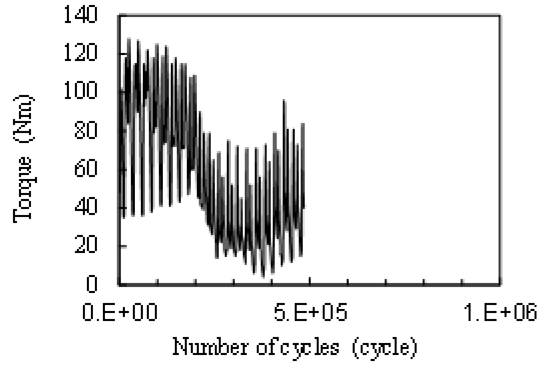


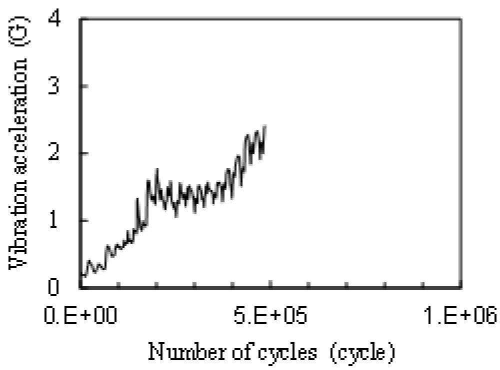


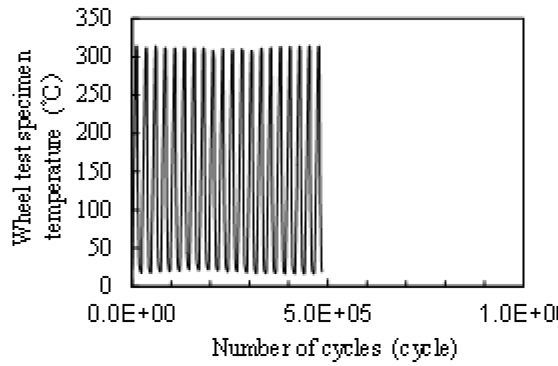


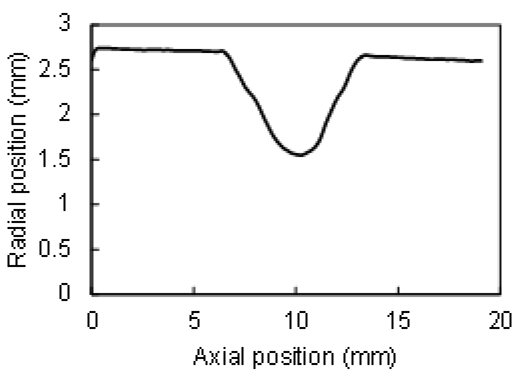
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
11	F3-3-1 (Wheel) 24 (Rail)	600	1.12	5		33.0	39.8
		RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		432,600	1,209.7	0.120	0.120	0.626	Minor shelling

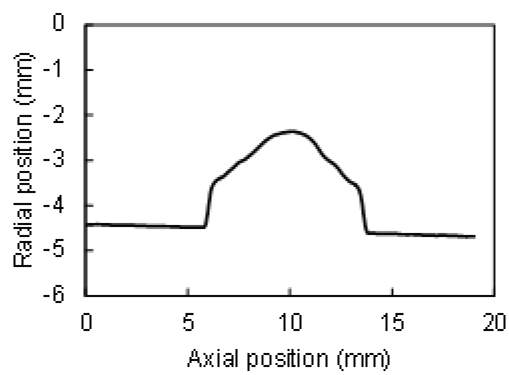


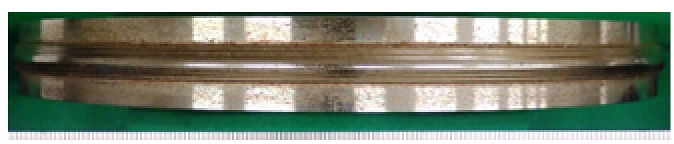




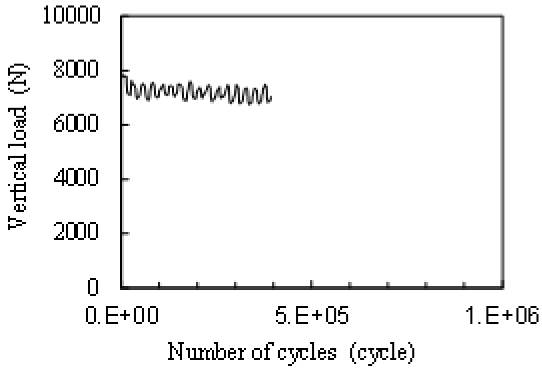


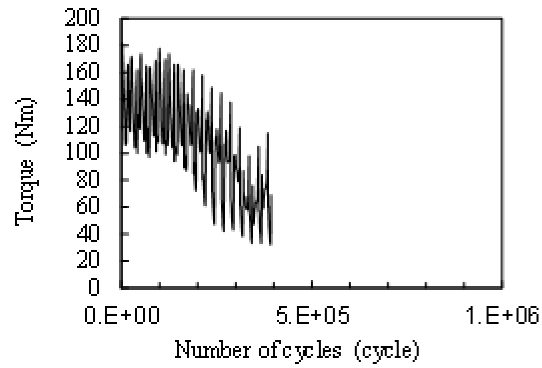


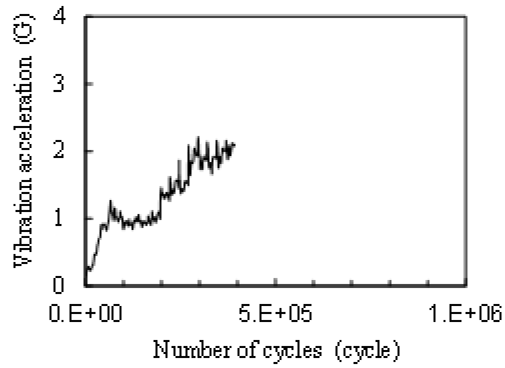


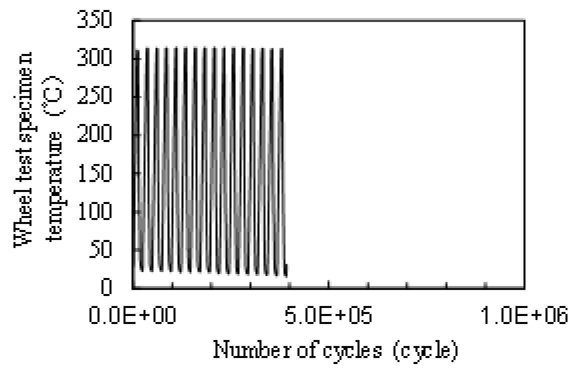


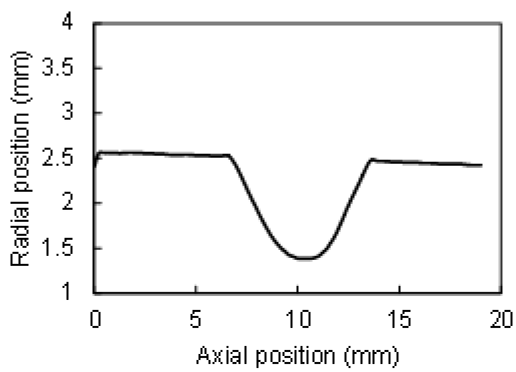
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
		600	1.11	5		35.5	38.6
31	C3-2-2 (Wheel) 25 (Rail)	RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		285,600	1,176.8	0.240	0.240	0.873	Minor shelling

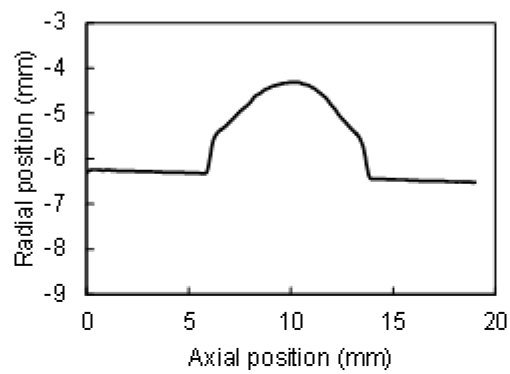


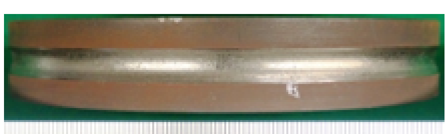


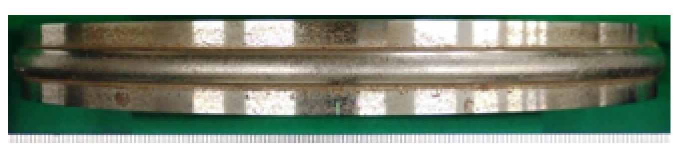




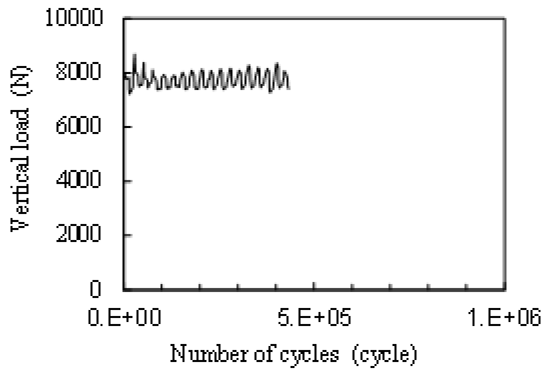


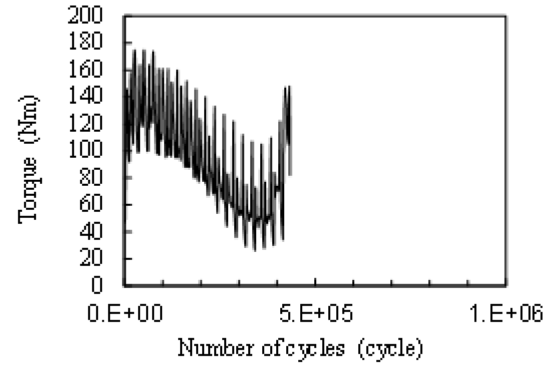


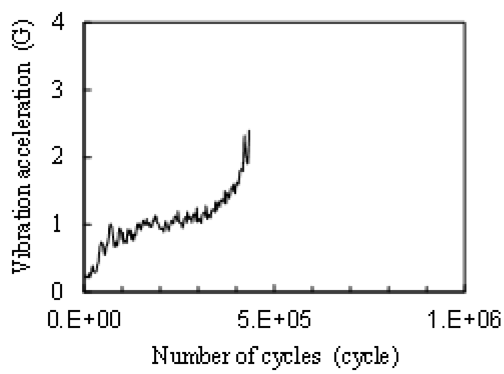


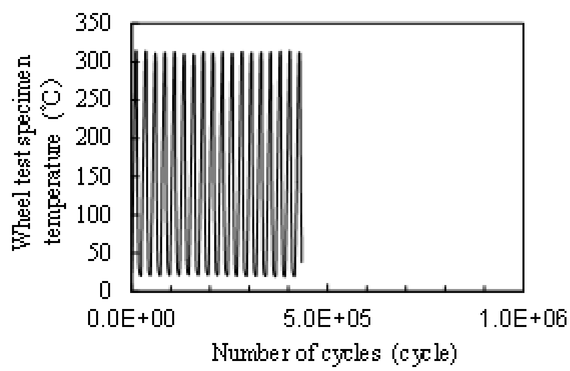


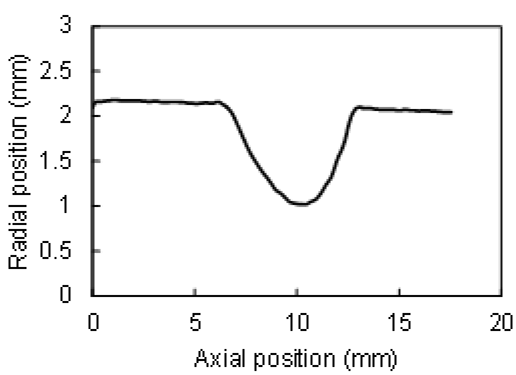
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC: Wheel	Hardness HRC: Rail
		600	1.08	5		32.3	38.4
15	F3-3-2 (Wheel) 26 (Rail)	RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient: Average	Traction coefficient: Average of absolute	Slip ratio [%]	Surface condition
		420,000	1,219.1	0.199	0.199	0.861	Shelling

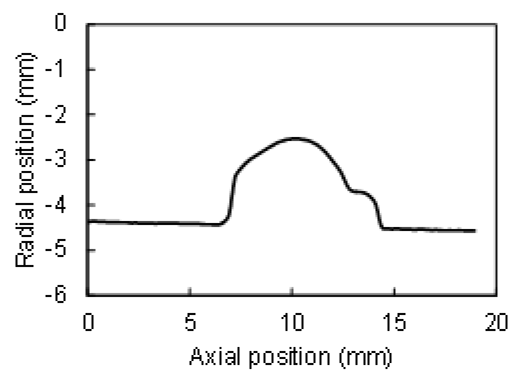


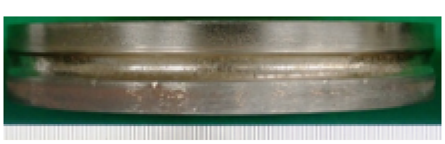


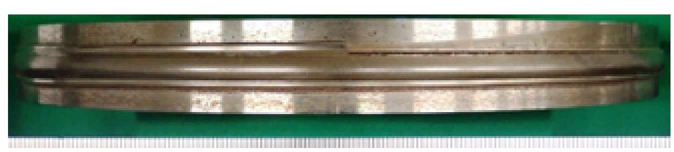




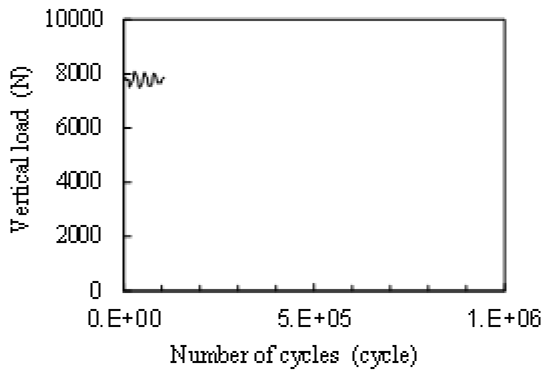


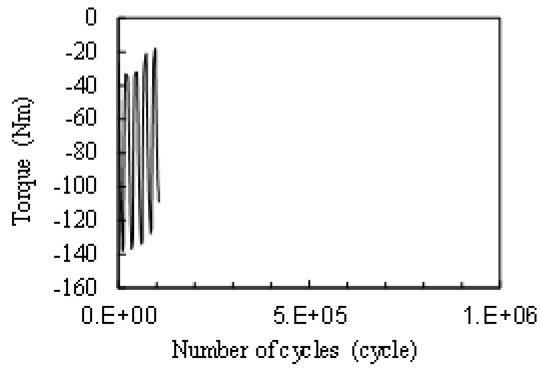


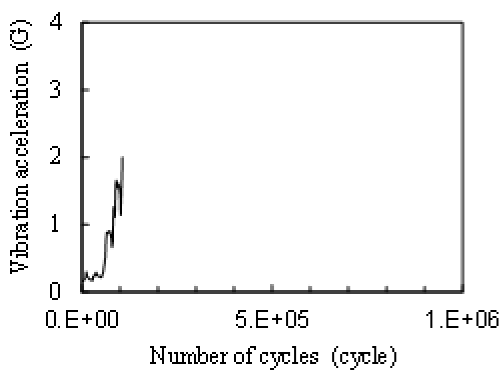


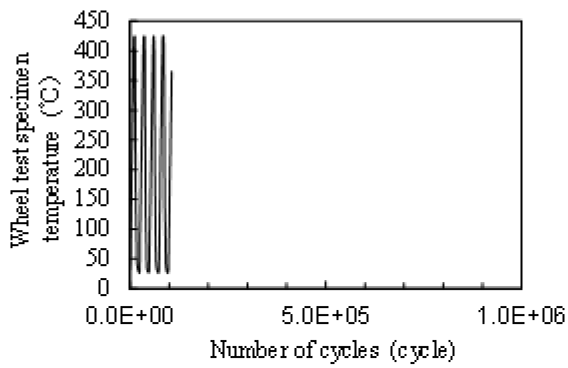


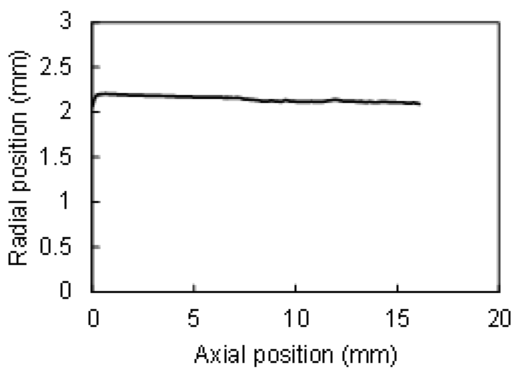
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
		800	0.13	5		35.0	39.7
20	C4-1-1 (Wheel) 28 (Rail)	RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		106,400	1,222.1	-0.162	0.162	0.156	Minor shelling

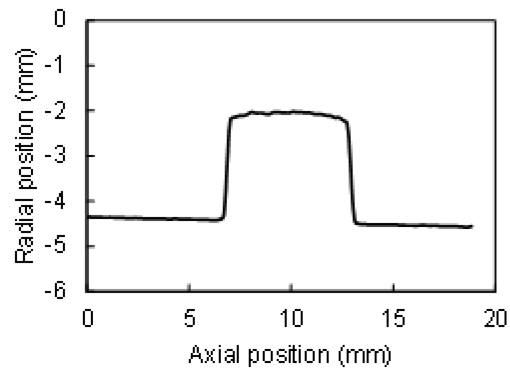


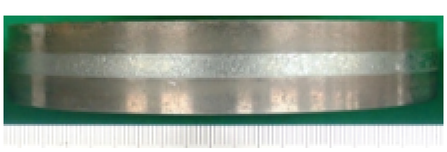


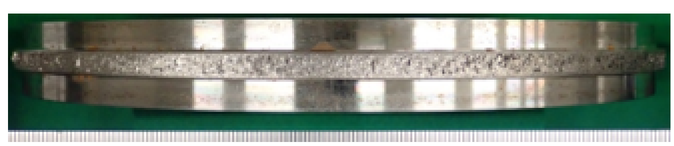




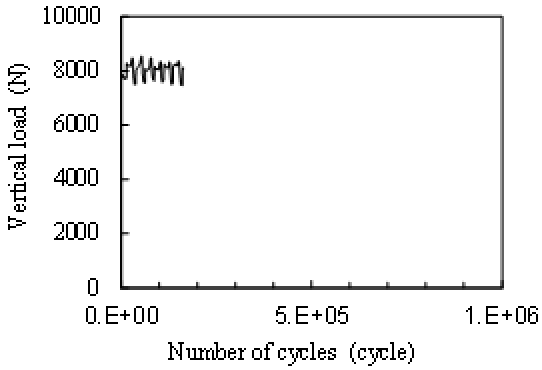


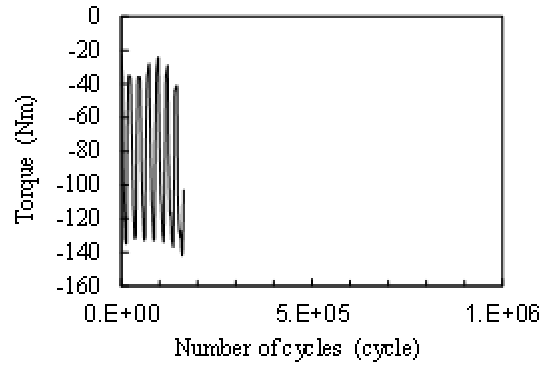


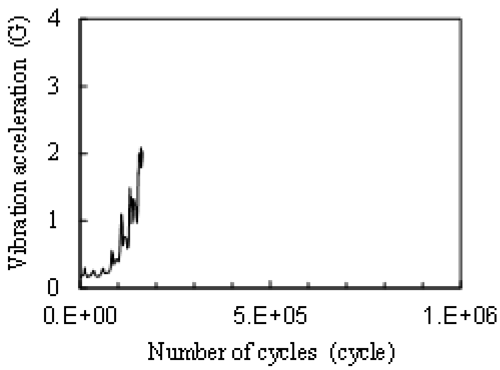


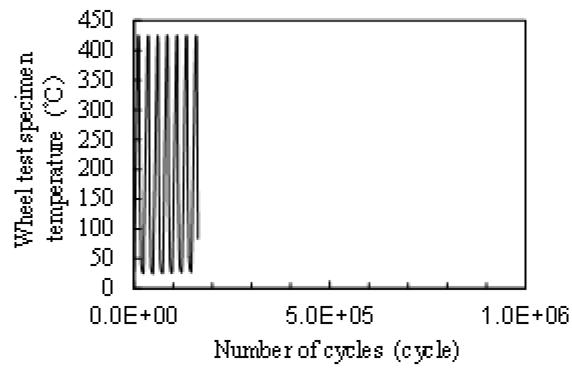


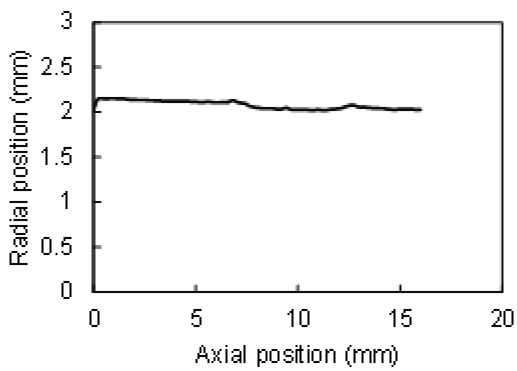
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
		800	0.10	5		31.8	38.6
4	F4-1-1 (Wheel) 29 (Rail)	RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		155,400	1,241.3	-0.177	0.177	0.137	Minor shelling

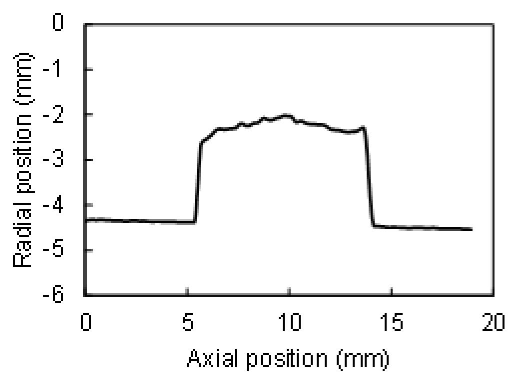


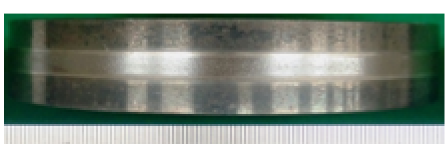




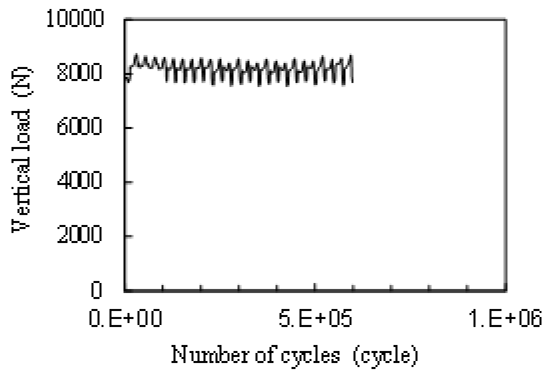


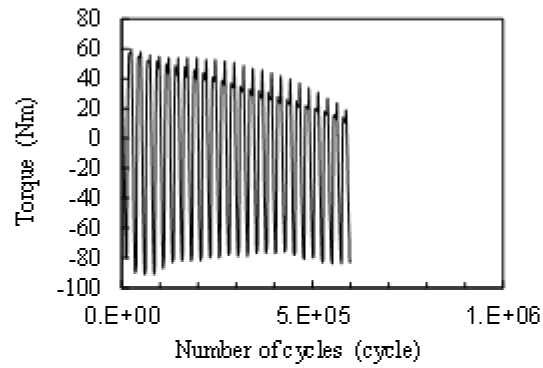


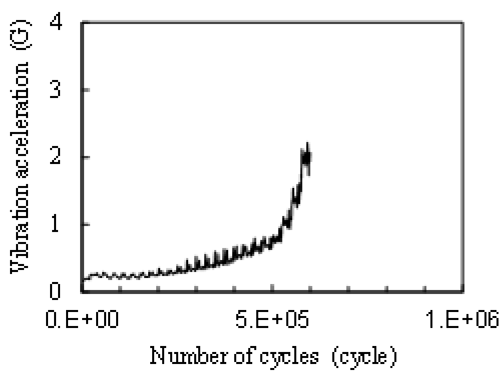


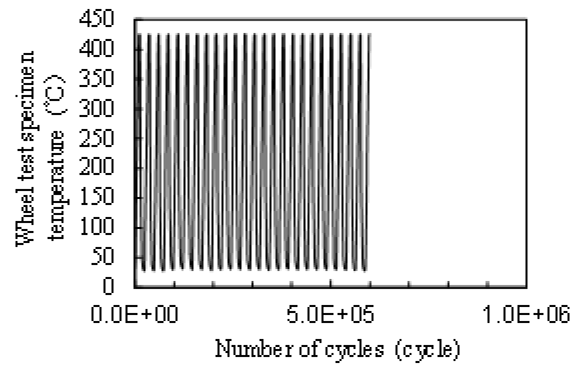


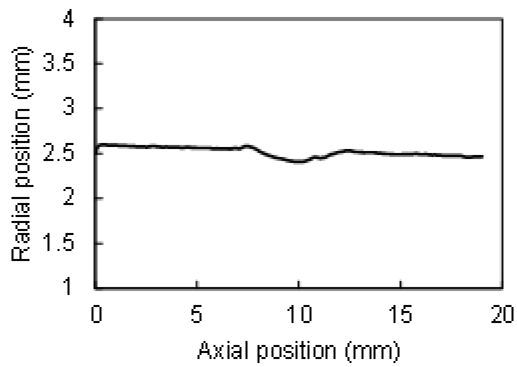
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
		800	0.12	5		33.1	39.9
24	C4-2-1 (Wheel) 31 (Rail)	RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		578,200	1,253.4	-0.016	0.085	0.384	Shelling

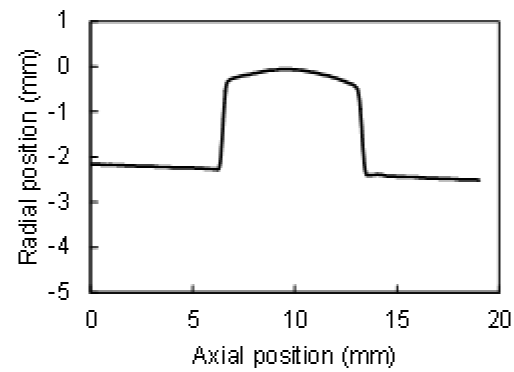


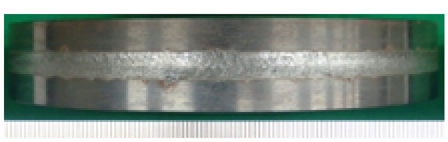


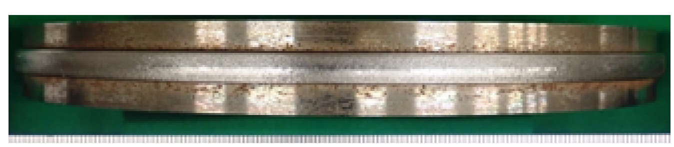




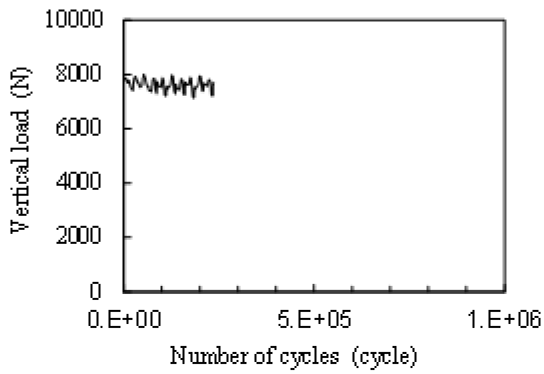


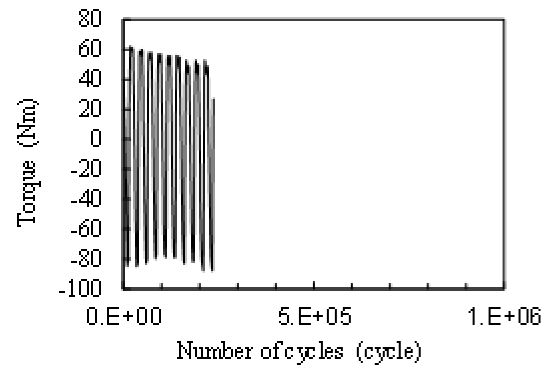


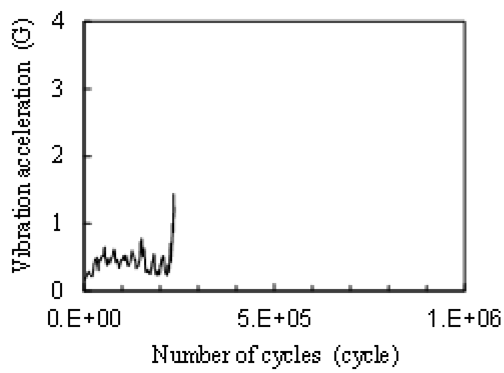


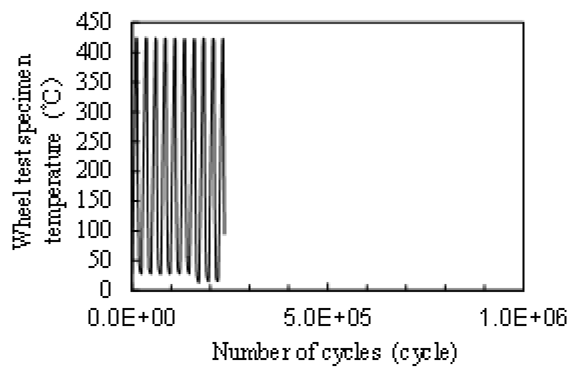


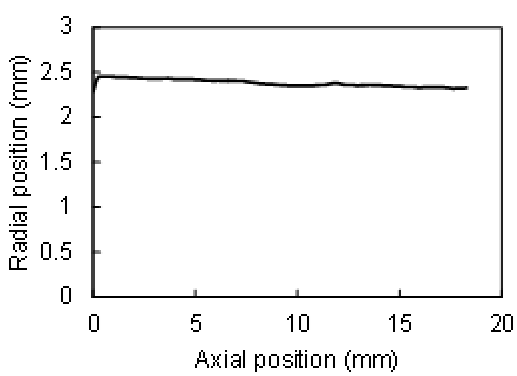
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
8	F3-4-1 (Wheel) 33 (Rail)	800	0.17	5		31.0	37.6
		RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		236,600	1,209.8	-0.006	0.107	0.378	Minor shelling

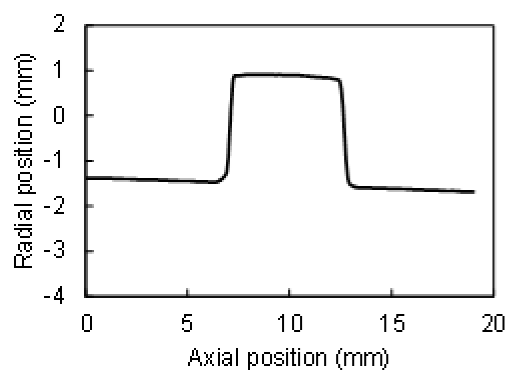


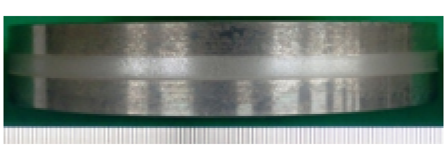


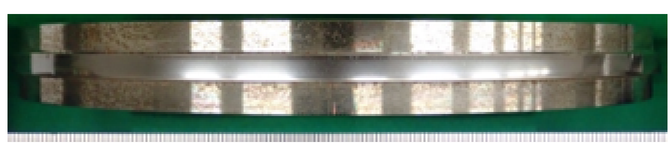




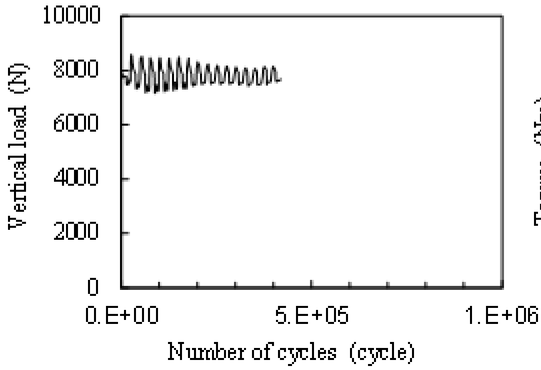


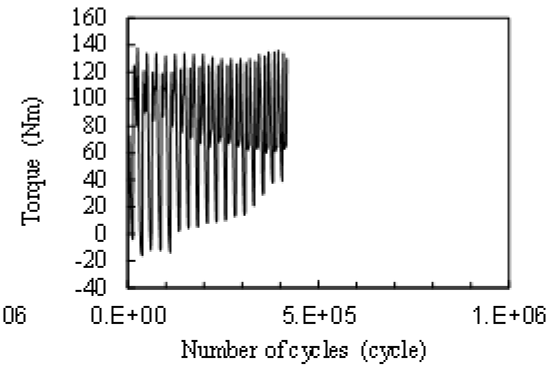


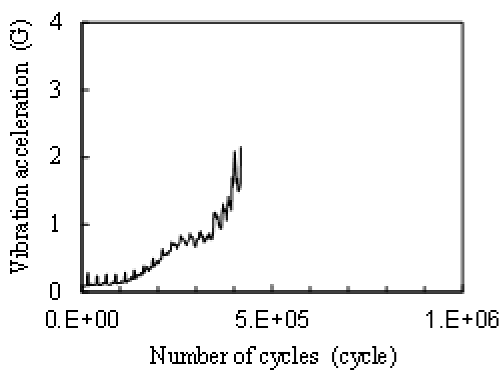


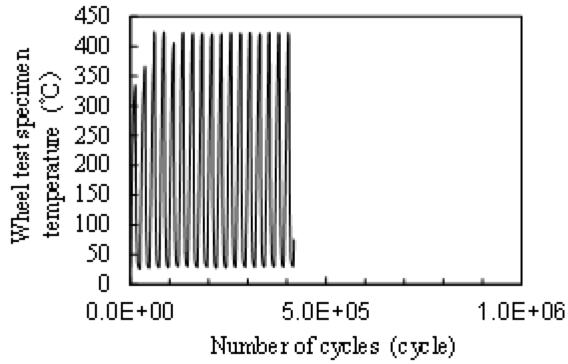


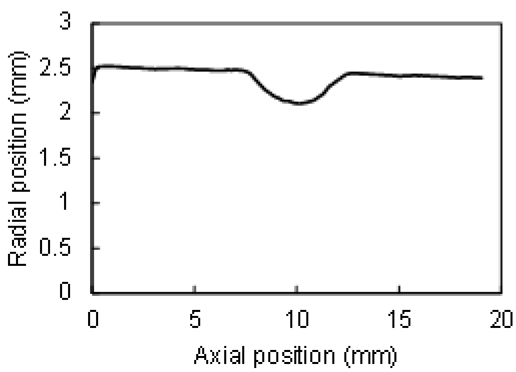
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
12	F3-4-2 (Wheel) 35 (Rail)	800	0.34	5		31.2	38.4
		RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		400,400	1,223.2	0.157	0.159	0.663	Shelling

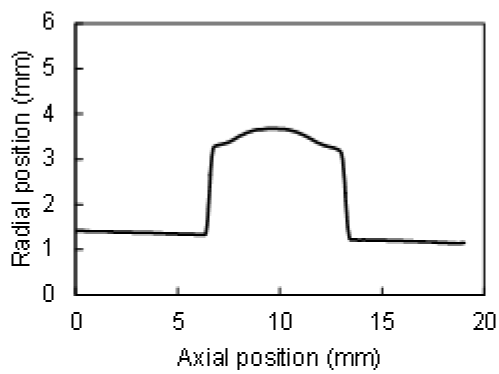


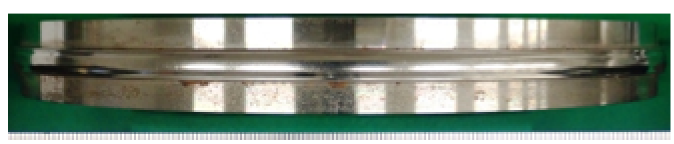












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<tr><td>Wheel</td><td>Rail</td></tr>
<tr><td>800</td><td>1.13</td><td colspan="2">5</td><td>35.4</td><td>38.1</td></tr>
<tr><td rowspan="3">28</td><td rowspan="3">C4-3-1 (Wheel) 36 (Rail)</td><td rowspan="2">RCF life [cycle]</td><td rowspan="2">Hertzian stress [MPa]</td><td colspan="2">Traction coefficient</td><td rowspan="2">Slip ratio [%]</td><td rowspan="2">Surface condition</td></tr>
<tr><td>Average</td><td>Average of absolute</td></tr>
<tr><td>497,700</td><td>1,195.5</td><td>0.107</td><td>0.110</td><td>0.662</td><td>Shelling</td></tr>
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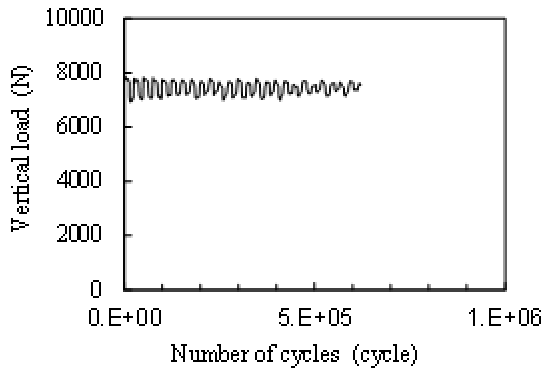
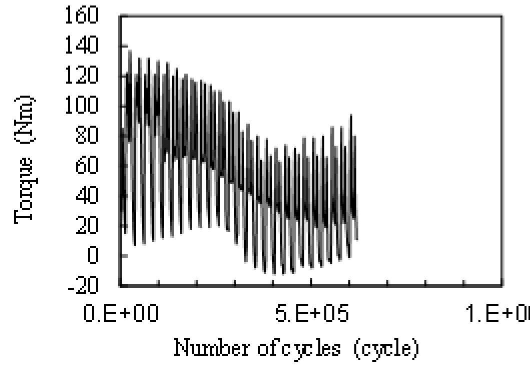
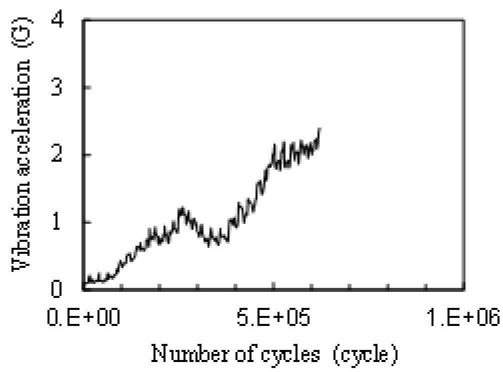
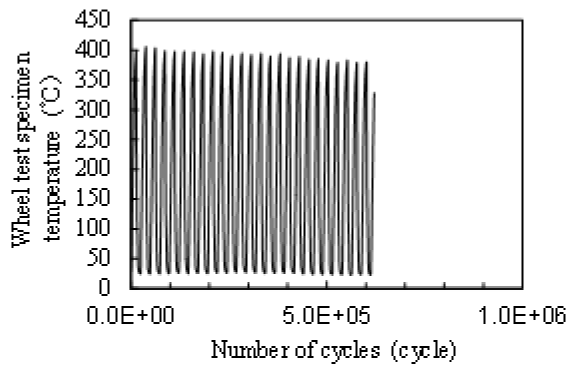
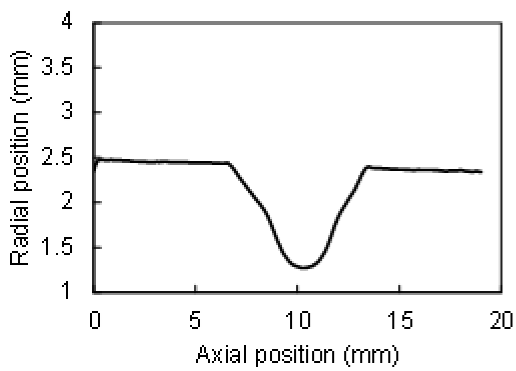
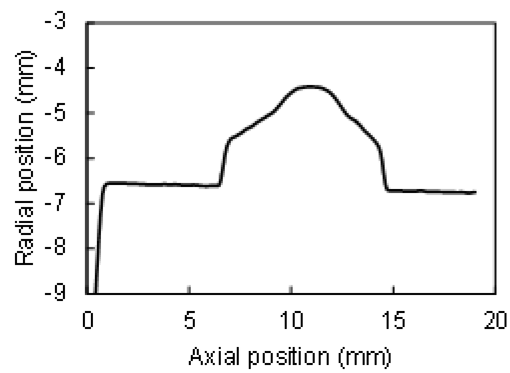


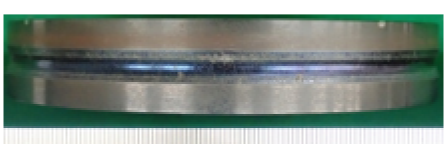


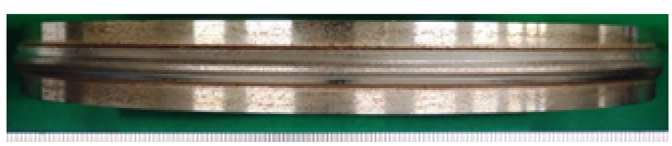




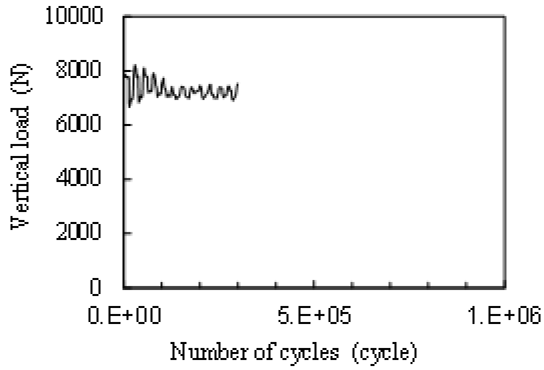


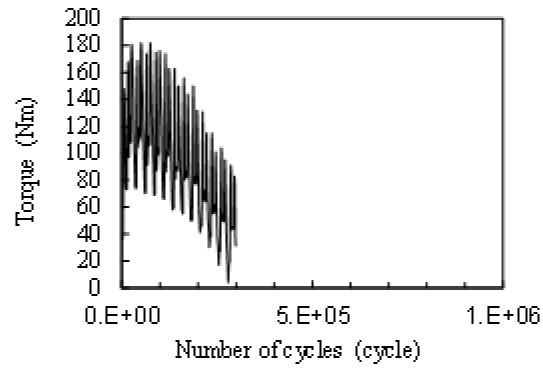


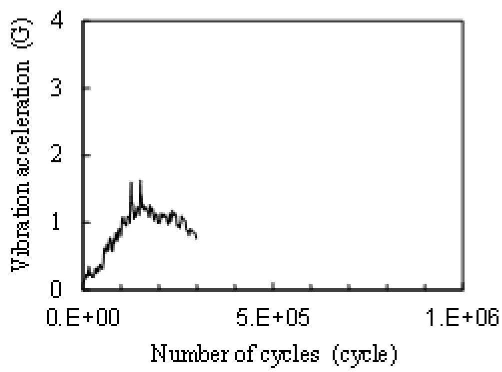


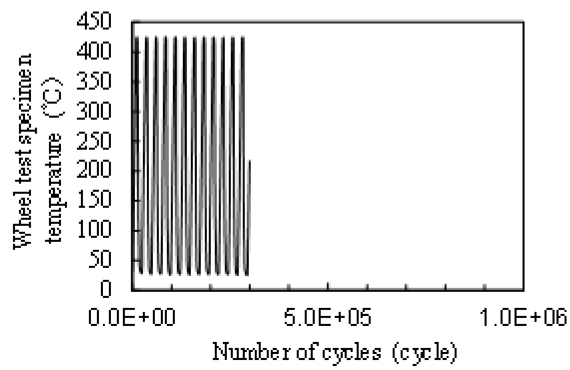


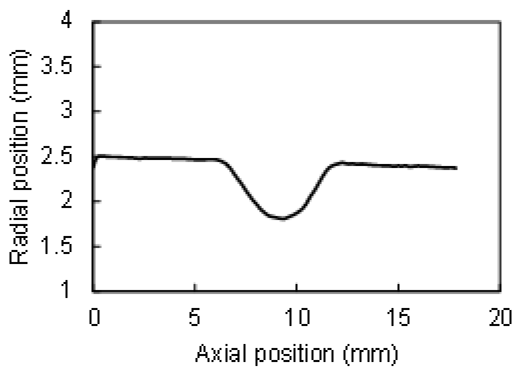
Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
		800	0.63	5		34.5	39.0
32	C2-2-1 (Wheel) 37 (Rail)	RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		298,900	1,184.1	0.208	0.208	0.897	Minor shelling

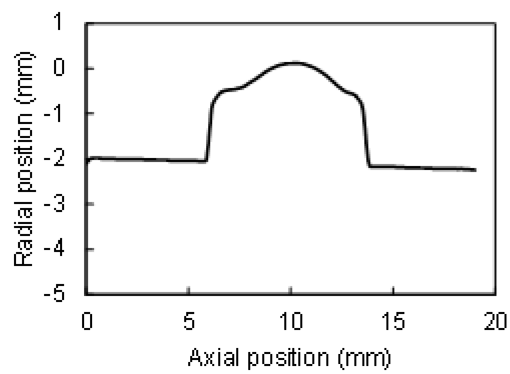


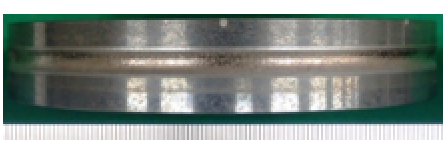


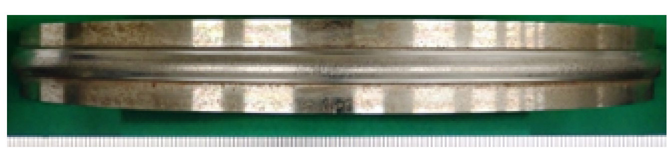












<table>
<tr><td rowspan="3">Test ID</td><td rowspan="3">Test specimen mark</td><td rowspan="2">Temperature [°F]</td><td rowspan="2">Wear depth [mm]</td><td rowspan="2" colspan="2">Contact width [mm]</td><td colspan="2">Hardness HRC</td></tr>
<tr><td>Wheel</td><td>Rail</td></tr>
<tr><td>800</td><td>2.06</td><td colspan="2">5</td><td>31.9</td><td>35.6</td></tr>
<tr><td rowspan="3">16</td><td rowspan="3">F4-1-2 (Wheel) 38 (Rail)</td><td rowspan="2">RCF life [cycle]</td><td rowspan="2">Hertzian stress [MPa]</td><td colspan="2">Traction coefficient</td><td rowspan="2">Slip ratio [%]</td><td rowspan="2">Surface condition</td></tr>
<tr><td>Average</td><td>Average of absolute</td></tr>
<tr><td>541,800</td><td>1,226.7</td><td>0.121</td><td>0.161</td><td>0.898</td><td>Minor shelling</td></tr>
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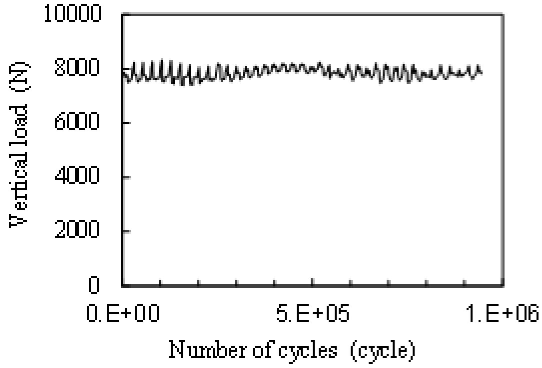
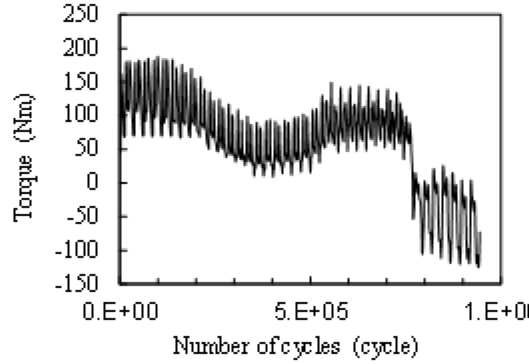
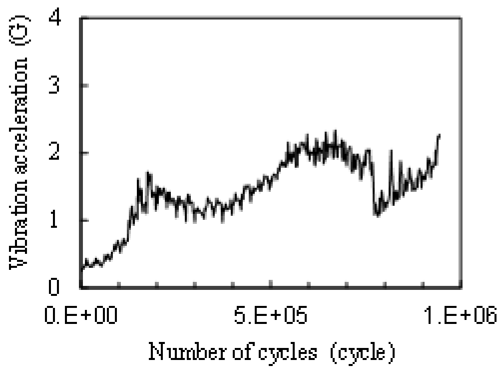
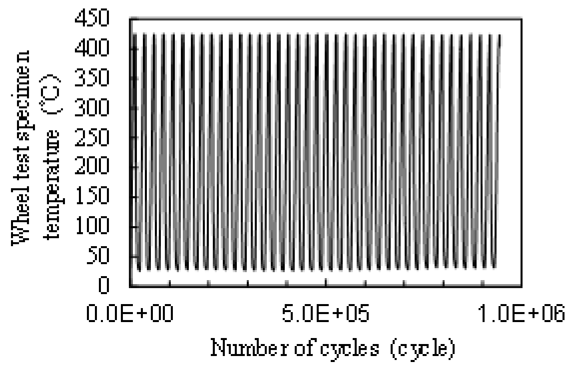
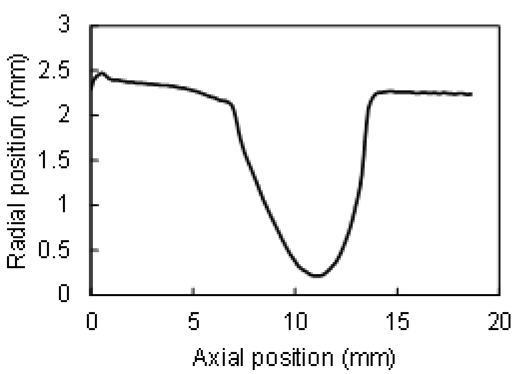
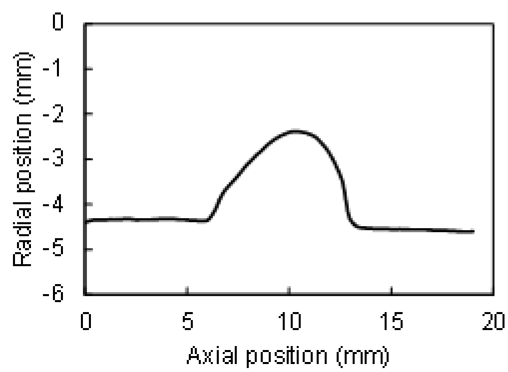


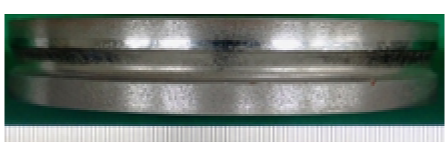


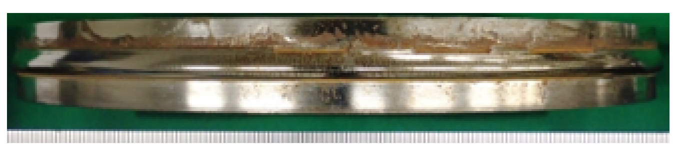






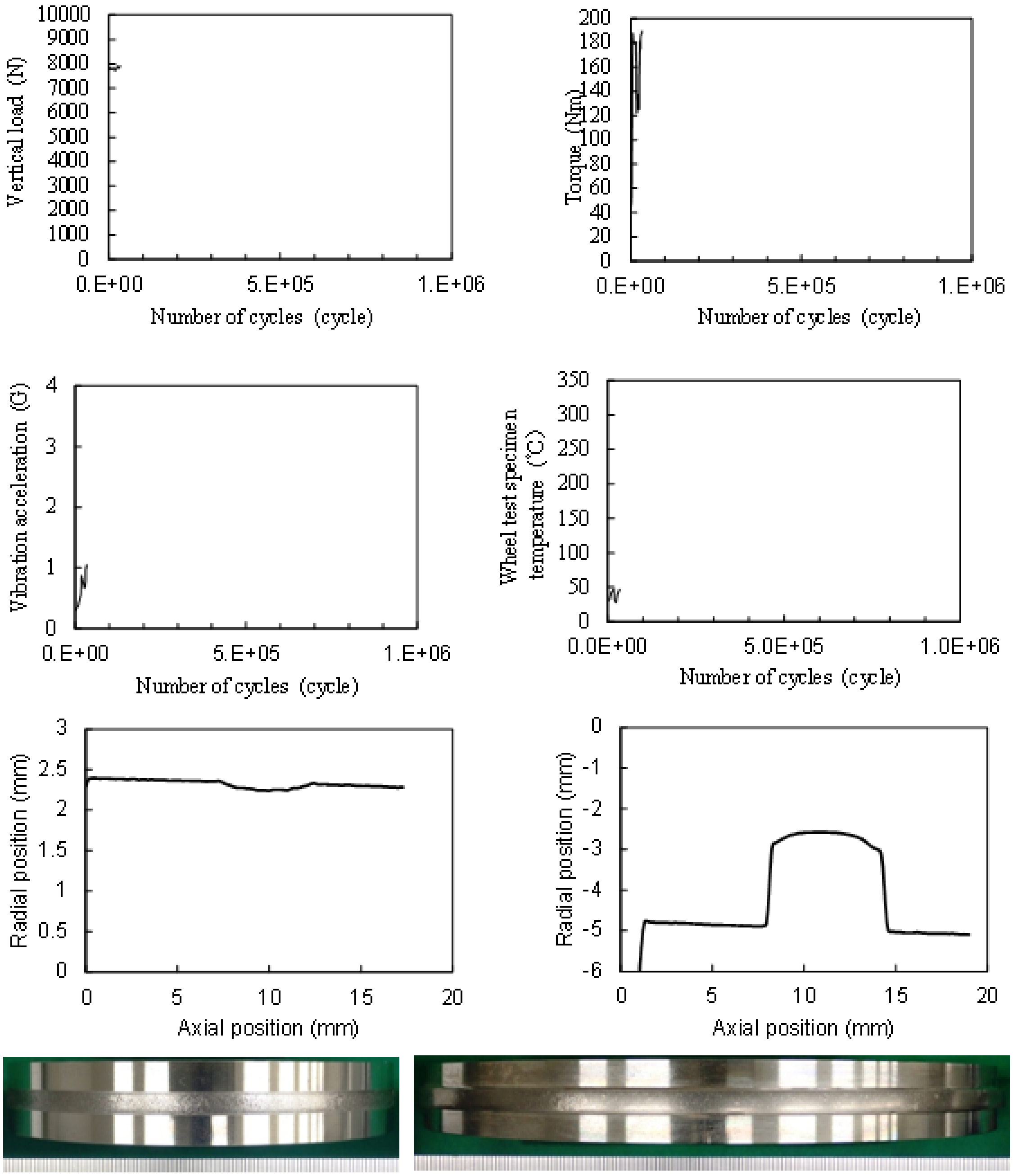






Test ID	Test specimen mark	Temperature [°F]	Wear depth [mm]	Contact width [mm]		Hardness HRC	
						Wheel	Rail
13	F4-2-2 (Wheel) 40 (Rail)	Ambient	0.13	5		31.3	40.9
		RCF life [cycle]	Hertzian stress [MPa]	Traction coefficient		Slip ratio [%]	Surface condition
				Average	Average of absolute		
		34,030	1,226.4	0.325	0.894	0.894	Shelling

Note: This test was terminated due to exceeding limitation of torque.



Vertical load (N)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0.E+00
5.E+05
1.E+06
Number of cycles (cycle)
Torque (Nm)
200
180
160
140
120
100
80
60
40
20
0
0.E+00
5.E+05
1.E+06
Number of cycles (cycle)
Vibration acceleration (G)
4
3
2
1
0
0.E+00
5.E+05
1.E+06
Number of cycles (cycle)
Wheel test specimen temperature (℃)
350
300
250
200
150
100
50
0
0.0E+00
5.0E+05
1.0E+06
Number of cycles (cycle)
Radial position (mm)
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
Axial position (mm)
Radial position (mm)
0
-1
-2
-3
-4
-5
-6
0
5
10
15
20
Axial position (mm)

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
AAR	Association of American Railroads
HB	Brinell Hardness
NSTEC	Nippon Steel Technology Co., Ltd.
HRC	Rockwell Hardness
RCF	Rolling Contact Fatigue
S_R	Slip Ratio
TTCI	Transportation Technology Center, Inc.