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Fatigue Behavior of Railcar Wheel Steel at Ambient and Elevated Temperature

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John A. Volpe National Transportation Systems Center
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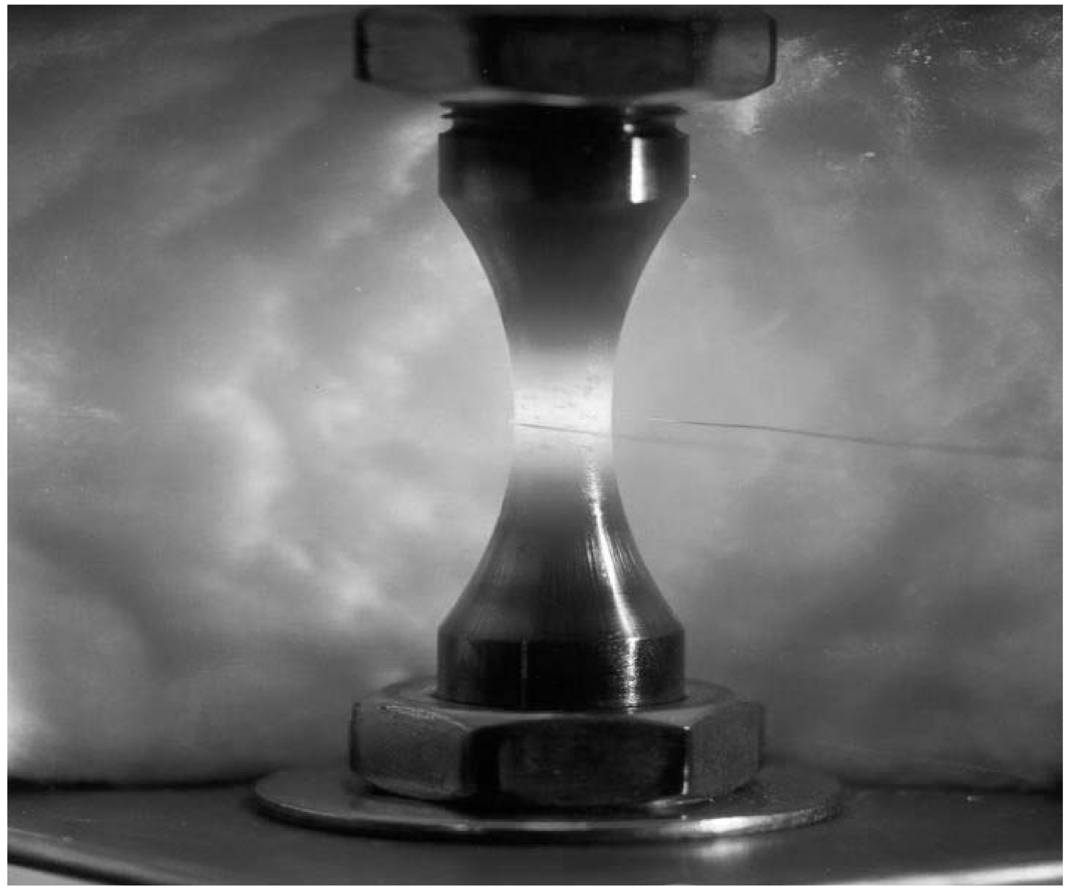

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13. ABSTRACT (Maximum 200 words)
This report presents the results of a material property test program undertaken on a Class B railcar wheel steel. This work was performed to obtain relevant fatigue data that may be used in support of a larger effort exploring the applicability of fatigue-based acceptance criteria for passenger and transit railroad wheels.

Classical stress-life (S-N) curves were developed for AAR Class B railcar wheel steel with specimens removed from the tread area of an as-forged railcar wheel. The specimen geometry was a standard hourglass fatigue test specimen with a low stress concentration (K_t) of 1.05. Fatigue testing was performed at stress ratios of –1.0, 0.05, 0.5, and 0.7. Testing was performed at ambient, 500°F, and 1000°F using high current resistance or convection methods. Endurance limit data was obtained for all R-ratios, although for the 1000°F condition there did not appear to be a clear endurance limit transition. These endurance limit data were used to estimate the Sines parameters, A and α.

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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

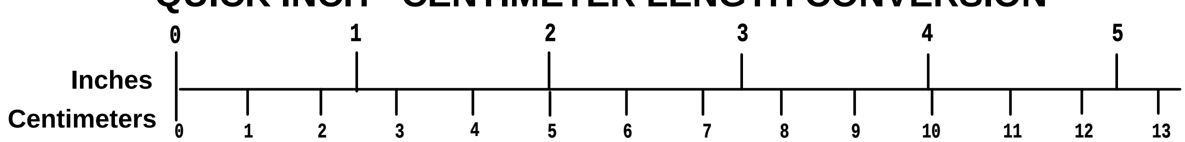
VOLUME (APPROXIMATE)

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 CONVERSION

°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

PREFACE

This report presents the results of a material property test program undertaken on a Class B wheel steel. This project has been carried out as part of the Federal Railroad Administration's (FRA) Rolling Stock and Components R&D Program,[1] under the direction of Ms. Claire L. Orth, Chief, Equipment and Operating Practices Research Division. Ms. Monique Stewart is the Project Manager for the research related to railroad wheel safety.

Mr. Jeff Gordon of the Volpe Center was the Contracting Officer's Technical Representative. The authors are grateful for the technical direction provided by Mr. Gordon and for his comments on the draft report. Thanks are also due to Dr. David Jeong of the Volpe Center for his review comments on the draft version of this report.

Gratitude is expressed to Dr. Gopal Samavedam (Foster-Miller) for overseeing this subcontract. Appreciation is further extended to Cameron Lonsdale (Standard Steel) for his efforts in procuring the wheels used herein. Dale Haines, Darryl Wagar, Forrest Campbell, and Wally Robledo from Southwest Research Institute (SwRI) all assisted in performing this testing. Finally, thanks to Loretta Mesa at SwRI for patiently preparing this manuscript.

[1] See Section 4.3, Rolling Stock and Components R&D in FRA's "Five Year Strategic Plan for Railroad Research, Development, and Demonstrations" at http://www.fra.dot.gov/rdv30/plan5yr/index.htm

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

A	Sines criteria material constant
K_t	Stress concentration factor
N	Cyclic fatigue life of a given specimen
P_i	Principle stress amplitude
R	Load ratio, ratio of minimum to maximum load
RA	Reduction of area at failure
S_i	Orthogonal mean stresses
S-N	Stress-life
ΔP	Load range applied to specimen
ΔS	Specimen section stress range (minimum diameter)
$\Delta\sigma$	Effective applied stress range
f_1	Amplitude of reversed axial stress
f_1'	Amplitude of fluctuating stress causing failure
α	Sines criteria material constant
ε	Percent elongation at failure
σ_{max}	Maximum applied stress level
σ_{UTS}	Ultimate tensile strength
σ_{YS}	0.2% yield strength
τ_{oct}	Octahedral shear stress

EXECUTIVE SUMMARY

Service loading conditions for railroad wheels include those due to wheel-on-rail contact as well as thermal loads from frictional heating during on-tread braking. Studies have shown that the wheel surface temperatures can reach 1000°F during stop-braking. Current wheel design acceptance criteria deal primarily with wheel designs for North American freight applications, whereas the American Public Transportation Association (APTA) Passenger Rail Equipment Safety Standards (PRESS) Committee is presently seeking to develop a companion fatigue-based standard for passenger and transit wheels.

The group developing the new standard is exploring the potential applicability of two fatigue-based acceptance criteria. However, no fatigue data exists for wheel steels, especially in the as-forged, service condition. In this report the results of a materials property test program is presented in detail, outlining the relevant chemical, tensile, and fatigue tests performed to enable characterization of a Class B wheel steel. Three temperatures were examined in this program and included ambient room temperature, 500°F, and 1000°F. The fatigue properties determined at ambient room temperature are required so as to address rail vehicle wheels equipped with disc brakes, which are not exposed to frictional heating during stop-braking. Fatigue testing was performed to determine the S-N curves for each of the three temperatures. Furthermore, a large number of fatigue tests were performed at R-ratios of -1.0 and 0.05 for each of the test temperatures to enable reliable estimates of the Sines parameters, A and α.

Chemical composition analysis indicated that both wheel samples were within the range for a Class B railroad wheel, as outlined in AAR specification M-107/208. Monotonic tensile tests were undertaken for the Class B wheel steel, at room temperature, 500°F, and 1000°F, with test results found to be in accordance with AAR baseline values, as given in AAR Standard S-660-83.

The majority of fatigue testing was performed at R-ratios of 1.0 and 0.05 to enable the full S-N curves to be developed. The remainder of testing was undertaken to obtain the endurance limit at 10^7 cycles for R-ratios of 0.5 and 0.7. The degree of scatter for fatigue tests averaged approximately one order of magnitude (10x) for all tests performed at replicate stress levels. Endurance limit data was obtained for all R-ratios at each of the three test temperatures. However, for the 1000°F tests there did not appear to be the usual endurance limit transition at the lower stress levels. Based on the endurance limit data for R-ratios of –1.0 and 0.05, an estimation of the Sines parameters, A and α, was obtained for each of the three test temperatures.

1. INTRODUCTION

The American Public Transportation Association (APTA) Passenger Rail Equipment Safety Standards (PRESS) Committee on wheel design is working toward the development of fitness-for-service design criteria for railroad wheels used in transit and passenger applications. Currently, wheel design acceptance criteria are specified in the Association of American Railroads' (AAR) Standard S-660 [1][1]. This standard deals primarily with wheel designs for North American freight applications, whereas the APTA Committee is presently seeking to develop a companion fatigue-based standard for passenger and transit railroad wheels.

The service loading conditions include those due to wheel-on-rail contact as well as thermal loads from frictional heating during on-tread braking. Studies at the Volpe National Transportation Systems Center [2] have shown that the wheel surface temperatures can reach 1000°F during stop-braking. Since the combination of contact and thermal loads results in multidimensional stresses in wheels, there is no standard way to apply conventional acceptance criteria.

The group developing the new standard is currently exploring the potential applicability of two fatigue-based acceptance criteria. Unfortunately, there is no fatigue data that exists for wheel steels, especially in the as-forged, service condition. The objective of this program is to determine the material properties (chemical composition, tensile, and fatigue), at ambient and elevated temperatures, of Class B wheel steel, as designated by the AAR. Although similar data will be required for Classes L, A, and C, this was beyond the scope of the current program. The three temperatures examined included ambient room temperature, 500°F, and 1000°F. The fatigue properties determined at ambient room temperature are required so as to address railroad vehicle wheels equipped with disc brakes, which are not exposed to frictional heating during stop-braking.

This report documents the procedures and results obtained from constant amplitude fatigue testing at Southwest Research Institute (SwRI®). The report will address issues associated with the procedures used during testing, including test specimen machining, and high-temperature test setup. Tabular and graphical descriptions of the results obtained, including estimates of fatigue parameters, and a discussion of the relevant trends and characteristics of the recorded data are then presented. Finally, the results are summarized in a concluding section that provides a brief review of the major findings. This project has been carried out as part of the Federal Railroad Administration's (FRA) Rolling Stock and Components R&D Program.[2]

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[1] Numbers in square brackets [ ] indicate references listed in Section 5.
[2] See Section 4.3, Rolling Stock and Components R&D in FRA's "Five Year Strategic Plan for Railroad Research, Development, and Demonstrations" at http://www.fra.dot.gov/rdv30/plan5yr/index.htm

2. MATERIAL, EXPERIMENTAL METHODS, AND DATA ANALYSIS

2.1 Material and Specimen Geometries

The AAR Class B railroad wheel steel used in this test program is designed for high-speed service with severe braking conditions and heavy wheel loads, when used under passenger car service conditions. The AAR Class B wheel steel required for constant amplitude fatigue testing was supplied from two railroad wheels, sectioned into eight pieces per wheel, as schematically shown in Figure 1. Specimens for tensile, chemical composition, and fatigue tests were extracted from each of the railroad wheels.

Individual sections from each of the two railroad wheels were selected to enable a tensile and chemical test sampling of both wheels. The two wheels were produced by Standard Steel of Burnham, Pennsylvania in March 2000 from steel heat P5407. The basic geometries generally conformed to the relevant ASTM test specification [3]. However, the actual specification used to determine properties evaluated, specimen geometry, and test procedures depended upon the type of test performed:

- Tensile testing: ASTM E8-00 (Standard Test Methods for Tension Testing of Metallic Materials),
- Fatigue testing: ASTM E466-96 (Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials).

The various standards allow for a number of specimen shapes and sizes depending upon requirements of the particular test and raw material form.

The tensile testing was subcontracted with specimen blanks supplied to the vendor. The blanks were machined into second-subsize specimens with gage length diameters of 0.250 inch, as illustrated in Figure 2. Second-subsize specimens were used to enable a larger number of specimens to be extracted from the wheel sections, as well as enabling the gage section to be machined as close to the rolling contact surface as possible. Elongation at failure was measured over the total gage length (1.0 inch) of the specimen. The tensile properties were determined only in the circumferential orientation for the railroad wheels, with this being the most relevant orientation in terms of the fatigue specimens. Schematics indicating how the tensile, chemical, and fatigue test specimens were positioned in the railroad wheel materials are illustrated in Figures 3 (tensile and chemical) and 4 (fatigue). The actual fatigue specimen geometry is shown in Figure 5.

A basic code was used to form the identification numbers of the fatigue specimens. This code typically consisted of a number identifying the railroad wheel, a letter denoting the wheel section, and then a multi-digit identifier qualitatively indicating position in the product, as outlined below:

- Wheel **0** (Serial No. 0-3-03960), **1** (Serial No. 0-3-03961),

- Wheel Section **A-H** (see Figure 1), and
- Specimen Position **1-10** (see Figure 4).

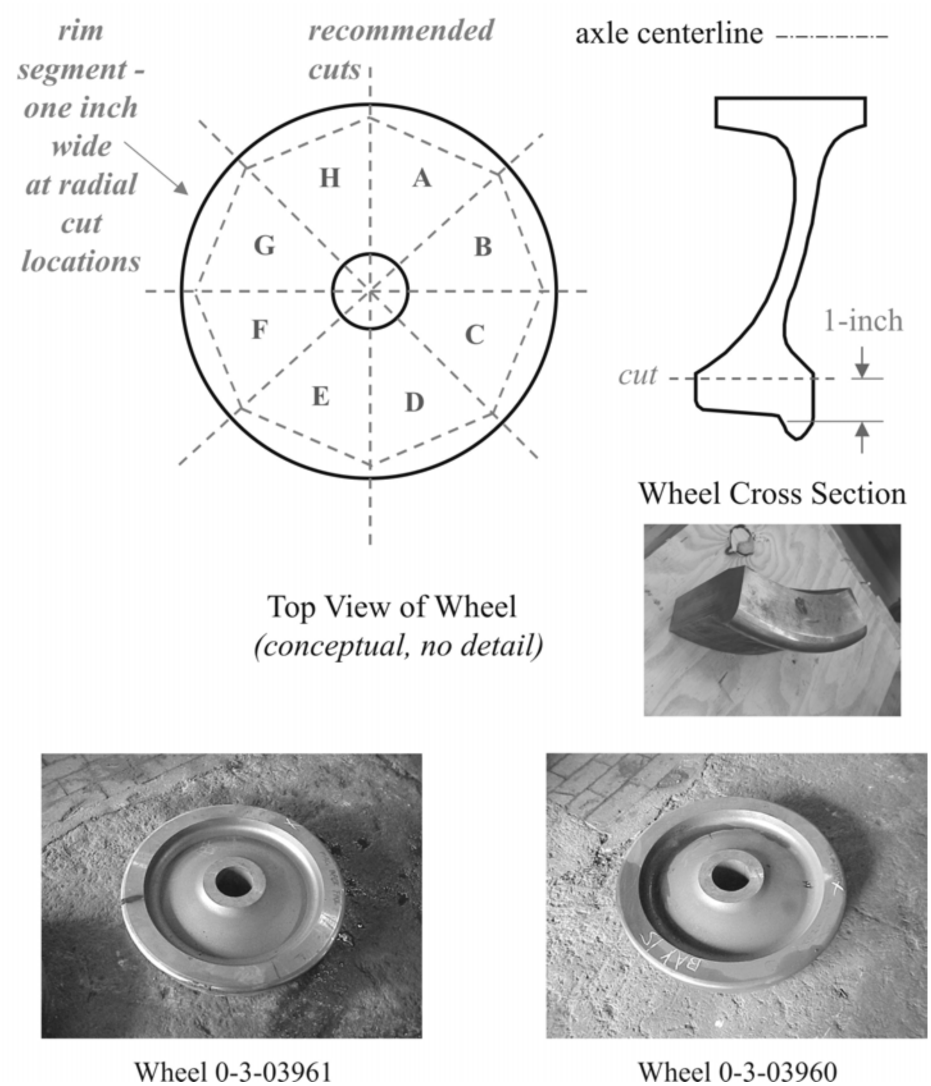

Figure 1. Schematic Showing Extraction of Sections from the Two Railroad Wheels

The two chemical test specimens were identified by 0 and 1, indicating the wheel from which they were extracted. Similarly, the tensile test specimens were identified numerically from 1 to 10, with their relevant position in the wheel shown in Figure 3. A complete list of specimens extracted from the two wheels is provided in Table 1.

2.2 Experimental Test Procedures

As indicated previously, testing was performed in accordance with the ASTM test specifications and supplemented by experience gained over many years of similar testing. The purpose of this section is to provide additional detail of the methods used during tensile, chemical, and fatigue testing.

Table 1. Description of the Specimens Used During Tensile, Chemical Composition, and Fatigue Testing

Wheel	Wheel Section	Fatigue Specimen ID	Tensile Specimen ID	Chemical Specimen ID
0-3-03960	A	0A1 *to* 0A10		
	B	0B1 *to* 0B10		
	C	0C1 *to* 0C10		
	D	0D1 *to* 0D10		
	E	0E1 *to* 0E10		
	F		1 *to* 6	0
	G	0G1 *to* 0G10		
	H	0H1 *to* 0H10		
0-3-03961	A	1A1 *to* 1A10		
	B	1B1 *to* 1B10		
	C		7 *to* 9	1
	D	1D1 *to* 1D10		
	E	1E1 *to* 1E10		
	F	1F1 *to* 1F10		
	G	SPARE WHEEL SECTION		
	H	1H1 *to* 1H10		

Tensile testing was performed completely in accordance with ASTM E8-00. Three specimens were tested at each of the specified test temperatures, namely room temperature, 500°F, and 1000°F, giving a total of nine tensile tests performed. The quantities recorded during testing or derived from data included:

- ultimate tensile strength (σ_{UTS}),
- yield strength (σ_{YS}),
- percent elongation at failure, and
- percent reduction in area at failure.

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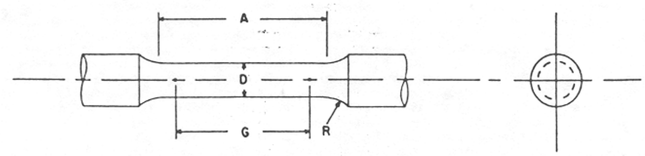


Dimensions					
	Standard Specimen	Small-Size Specimens Proportional to Standard			
	in.	in.	in.	in.	in.
Nominal Diameter	0.500	0.350	0.250	0.160	0.113
G—Gage length	2.000 ± 0.005	1.400 ± 0.005	1.000 ± 0.005	0.640 ± 0.005	0.450 ± 0.005
D—Diameter (Note 1)	0.500 ± 0.010	0.350 ± 0.007	0.250 ± 0.005	0.160 ± 0.003	0.113 ± 0.002
R—Radius of fillet, min	3/8	1/4	3/16	5/32	3/32
A—Length of reduced section, min (Note 2)	2 1/4	1 3/4	1 1/4	3/4	5/8

Figure 2. Specimen Geometry Utilized for Assessing Tensile Strength of the Wheel Material at 72°F, 500°F, and 1000°F (Extracted from ASTM Standard E8 [3])

Chemical analysis was performed on each of the two railroad wheels to provide verification that the material was within the specification for AAR M107/208 Class B wheel steel. The analysis was performed in accordance with the standard ASTM test specifications [4,5].

The vast majority of testing was concerned with evaluating the fatigue behavior of the Class B wheel steel under each of the three test temperatures. Four different R-ratios were to be evaluated during fatigue testing and included R = -1.0, 0.05, 0.5, and 0.7. The testing at R = -1.0 and R = 0.05 included sufficient specimens to generate the complete S-N curve. However, the testing at the other higher R-ratio conditions, R = 0.5 and R = 0.7, included only three specimens, nominally to determine the endurance limit. Due to the difficulty in determining the endurance limit at the higher R-ratios, the total number of specimens used at these higher R-ratios was increased from the originally allotted three specimens. However, conservative testing at the lower R-ratios of –1.0 and 0.05 reduced the number of specimens required to obtain the fatigue (S-N) curve, thus enabling a number of spare specimens to become available for further testing at the high R-ratios. Further details will be provided in the results and discussion sections.

The fatigue testing was performed in the Solid and Fracture Mechanics Laboratory at SwRI using three closed-loop, servo-hydraulic test frames, with high-temperature furnaces required for the 500°F and 1000°F tests. A photograph of the high-temperature test set-up for both the 500°F and 1000°F tests is shown in Figure 6. An overall view of the test set-up, illustrating the complexity and multiple components, is shown in Figure 7. Furthermore, two other 500°F test frames were set up utilizing a convection heating clam-shell arrangement, as shown in Figure 8. This enabled both 500°F and 1000°F tests to be performed in parallel. As shown in Figure 7 a step-down transformer was used to provide a variable high current, through water-cooled cables, to the heating plates. The high-temperature system provided very controlled and stable test specimen temperature. Prior to starting each fatigue test, the controller set temperature was gradually increased to the desired level to avoid any temperature overshoot that may occur in the specimen during heating.

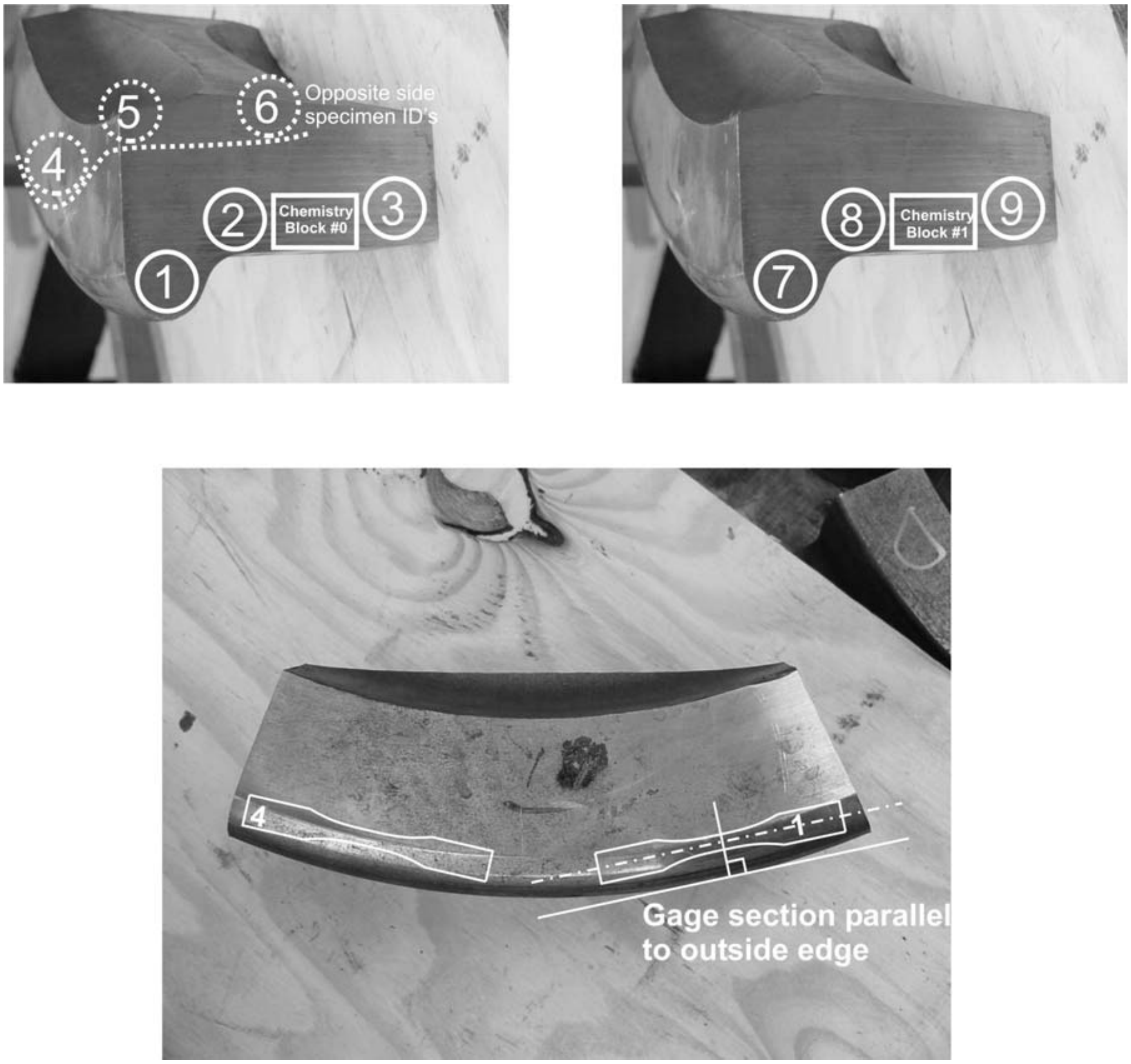


Figure 3. Schematic Layout for the Tensile and Chemical Composition Specimens

Testing frequency was in the range of 10-25Hz, with test frequency dependent primarily on the R-ratio. All specimens were tested until failure (two-pieces) or until the runout level of 10 million cycles was reached.

2.3 Fatigue-Based Criteria

The two fatigue-based acceptance criteria currently under consideration by the APTA PRESS Committee are the Sines criterion [6] and the French Societé Nationale des Chemins de Fer (SNCF) criterion [7]. The purpose of this section is to provide additional detail of the two criteria. Although the fatigue testing program described in the previous sections is primarily concerned with generating S-N curves for the Class B wheel steel, it is expected that material constants required in the Sines criterion will be able to be extracted from the experimental data.

Figure 4. Schematic Layout for the Fatigue Specimens in Each of the Wheel Sections

2.3.1 The Sines Criterion

In 1955, Sines [6] reviewed the results of experiments on the effect of different combinations of tensile, compressive, and torsional mean and alternating stresses on fatigue life. He reported that the alternating of shear stresses seemed to cause fatigue failure. Because of this, the influence of mean static stresses on the planes of maximum shear alternation was studied. From this study, Sines developed the relationship:

$$\frac{1}{3}\sqrt{(P_1 - P_2)^2 + (P_2 - P_3)^2 + (P_1 - P_3)^2} + \alpha\left(S_x + S_y + S_z\right) \leq A \qquad (1)$$

Where P_1, P_2, P_3 = amplitudes of the alternating principle stresses
S_x, S_y, S_z = orthogonal (any coordinate system) mean stresses
A = material constant proportional to reversed fatigue strength
α = material constant, which gives variation of the permissible range of stress with static stress

A and α are material properties for a given life level.

The first term on the left-hand side of Eq. 1 is the octahedral shear stress, τ_{oct}. Sines suggested that τ_{oct} averages the effect of shear stresses on many differently oriented slip planes. In addition, a hydrostatic stress term is included in this model by the second term on the left-hand side of Eq. 1.

The constants A and α may easily be determined from fatigue tests with a large R-ratio difference. For example, in a fully reversed uniaxial test, Eq. 1 is

$$\frac{\sqrt{2}}{3} P_1 = A \qquad (P_2 = P_3 = S_x = S_y = S_z = 0) \qquad (2)$$

Letting $P_1 = f_1$ gives

$$A = \frac{\sqrt{2}}{3} f_1 \tag{3}$$

where f_1 is the amplitude of reversed axial stress that would cause failure at the desired cyclic load. For 0 to σ_{max} loading (R-ratio = 0), Eq. 1 becomes

$$\begin{aligned} S'_x &= P'_1 \qquad (P'_2 = P'_3 = S'_y = S'_z = 0) \\ \frac{\sqrt{2}}{3} P'_1 &= A - \alpha P'_1 \end{aligned} \tag{4}$$

Letting $P'_1 = f'_1$ yields

$$\alpha = \frac{A}{P'_1} - \frac{\sqrt{2}}{3} = \frac{\sqrt{2}}{3}\left(\frac{f_1}{f'_1} - 1\right) \tag{5}$$

where f'_1 is the amplitude of fluctuating stress that would cause failure at the same cyclic life as f_1. Thus A and a are described in terms of stress amplitudes, f_1 and f'_1.

2.3.2 The SNCF Criterion

The second criterion currently under consideration is a modified Goodman diagram (MGD) as specified by the SNCF in its wheel design specification [7]. A graphical example of the SNCF modified Goodman diagram is shown in Figure 9. The mean and alternating stresses in this case are the radial stresses in the plate and plate fillet of the railroad wheel.

The truncation of the MGD is based on empirical data gained from SNCF experience in designing wheels for rail applications. Finite element analysis, under both mechanical and thermal loading, is used to evaluate railroad wheel designs prior to introducing them to service. The largest values of the radial stresses, predicted using finite element analysis, are used to calculate the mean and alternating radial stresses at each node in the model, as follows:

$$\sigma R_{mean} = \frac{(\sigma R_{\max} + \sigma R_{\min})}{2} \quad \text{and} \quad \sigma R_{alternating} = \frac{(\sigma R_{\max} - \sigma R_{\min})}{2} \tag{6}$$

The mean and alternating stress pairs are then plotted on the graph shown in Figure 9 for each node in the finite element model. To enable the proposed wheel design to be accepted for service all results must fall with the prescribed MGD envelope.

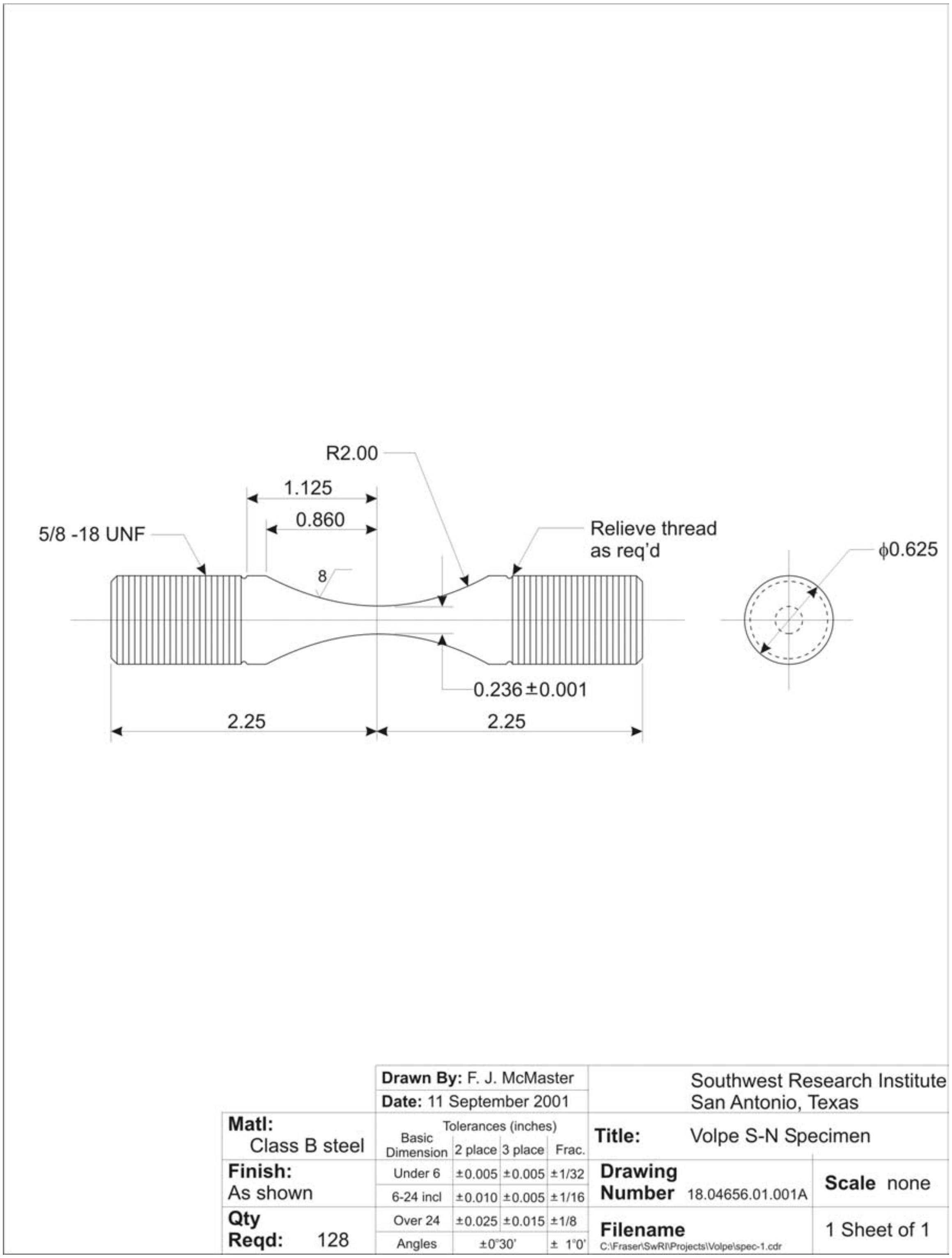


Figure 5. Design Drawing for the Hourglass Fatigue Specimen

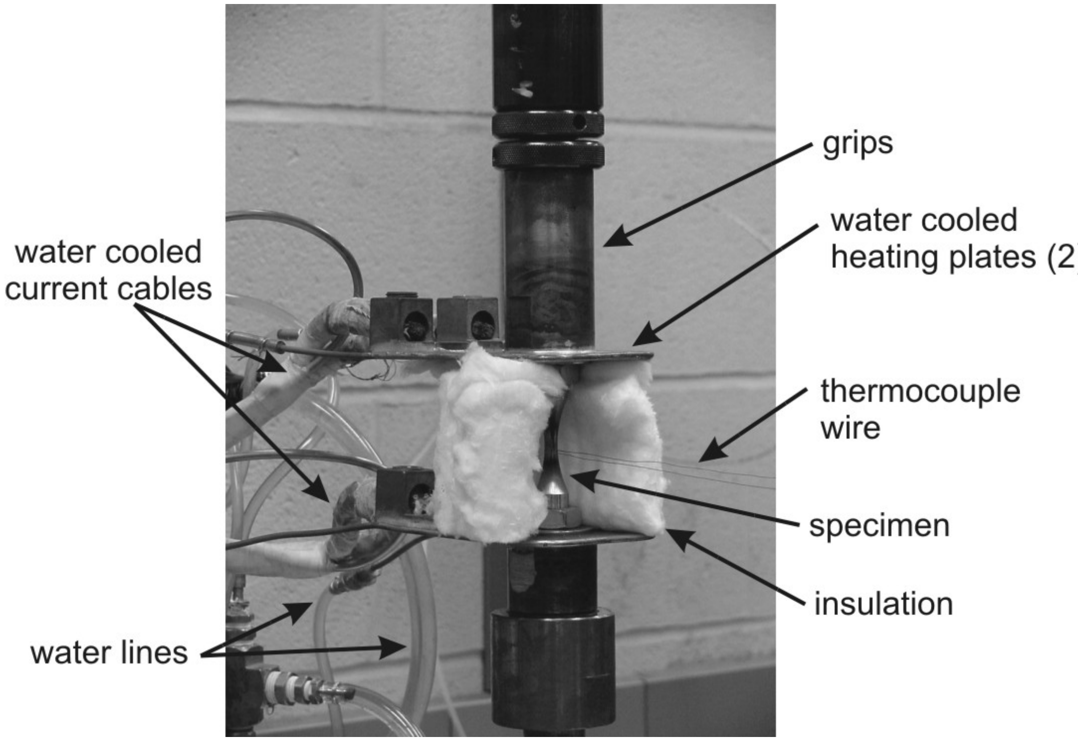


Figure 6. Detailed View of Set-up for 500°F and 1000°F High-temperature S-N Fatigue Testing

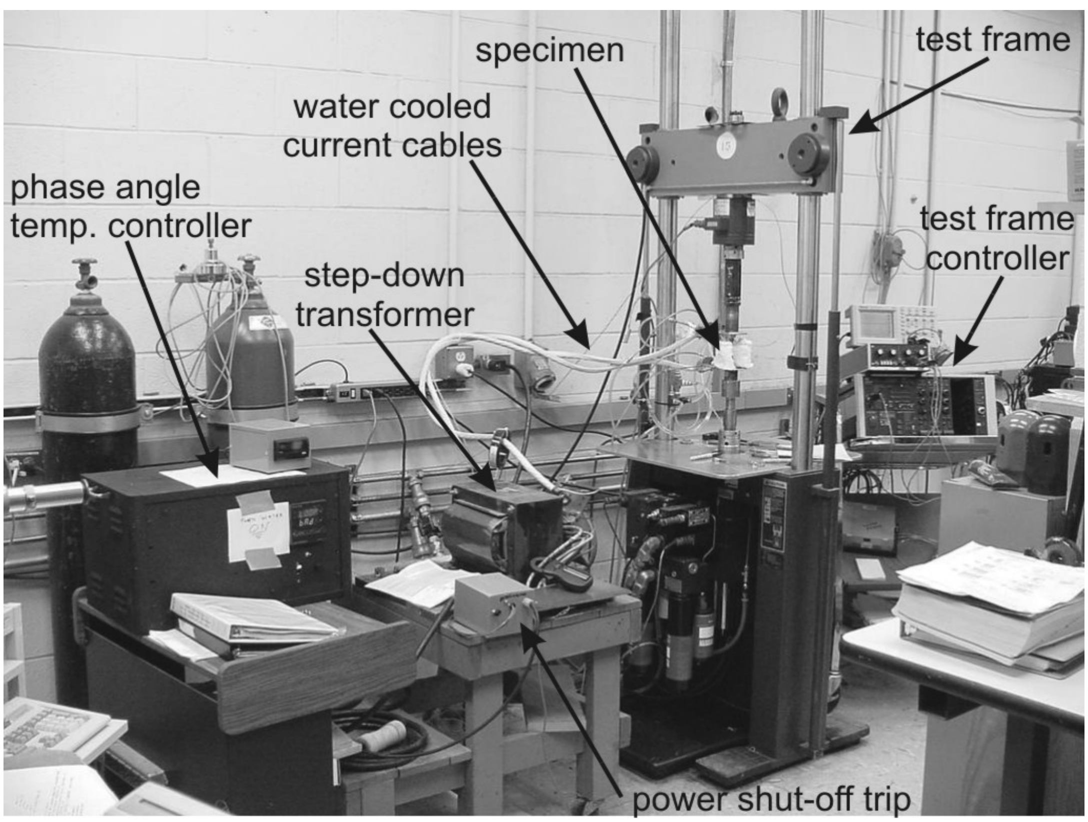
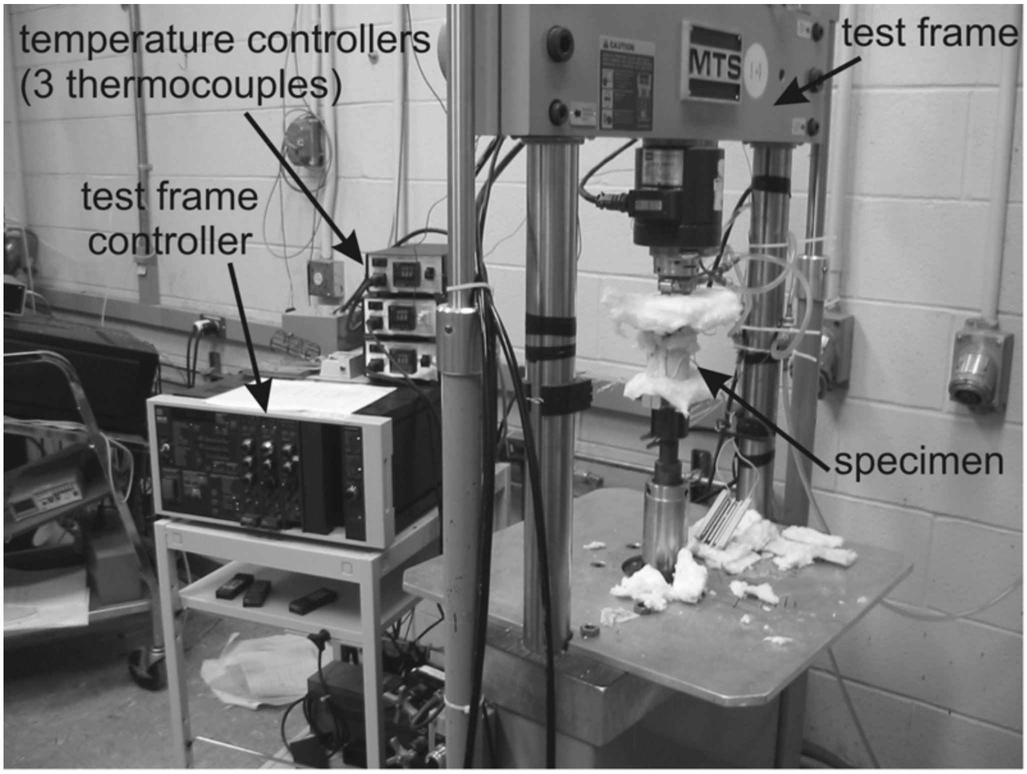


Figure 7. Overall Set-up for High-temperature S-N Fatigue Testing



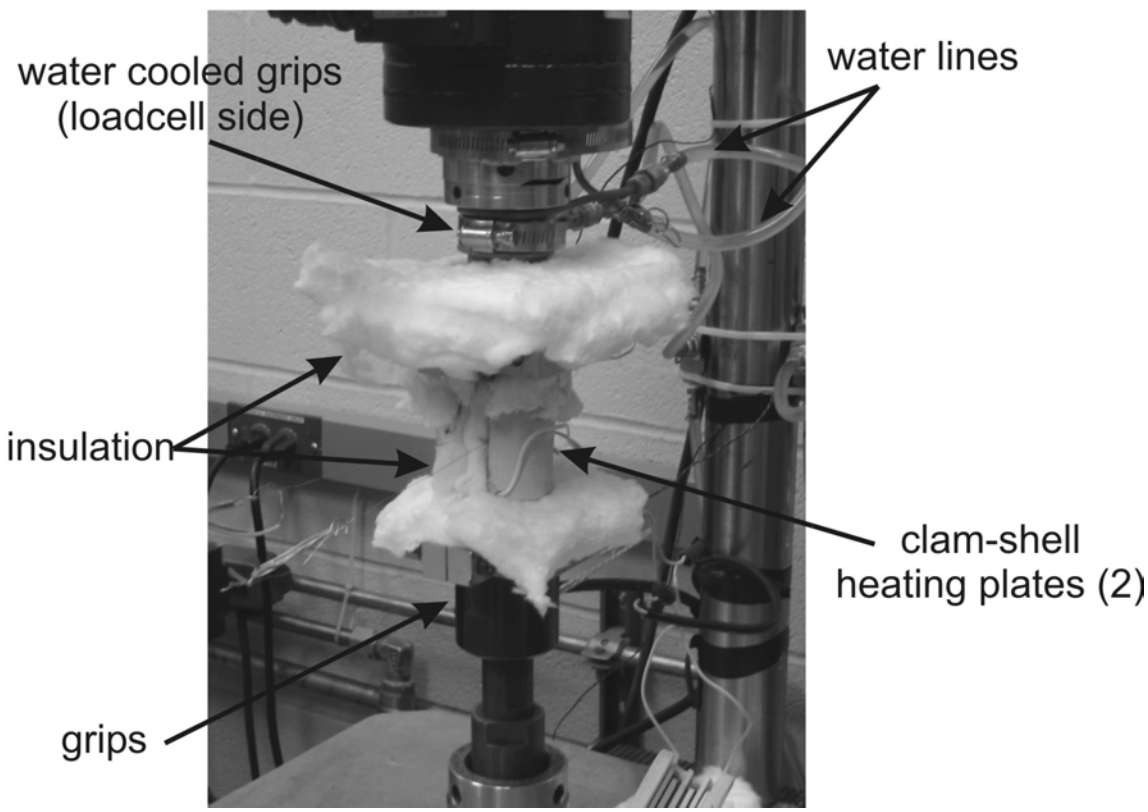


Figure 8. Alternative Test Set-up Used for 500°F High-temperature S-N Fatigue Testing

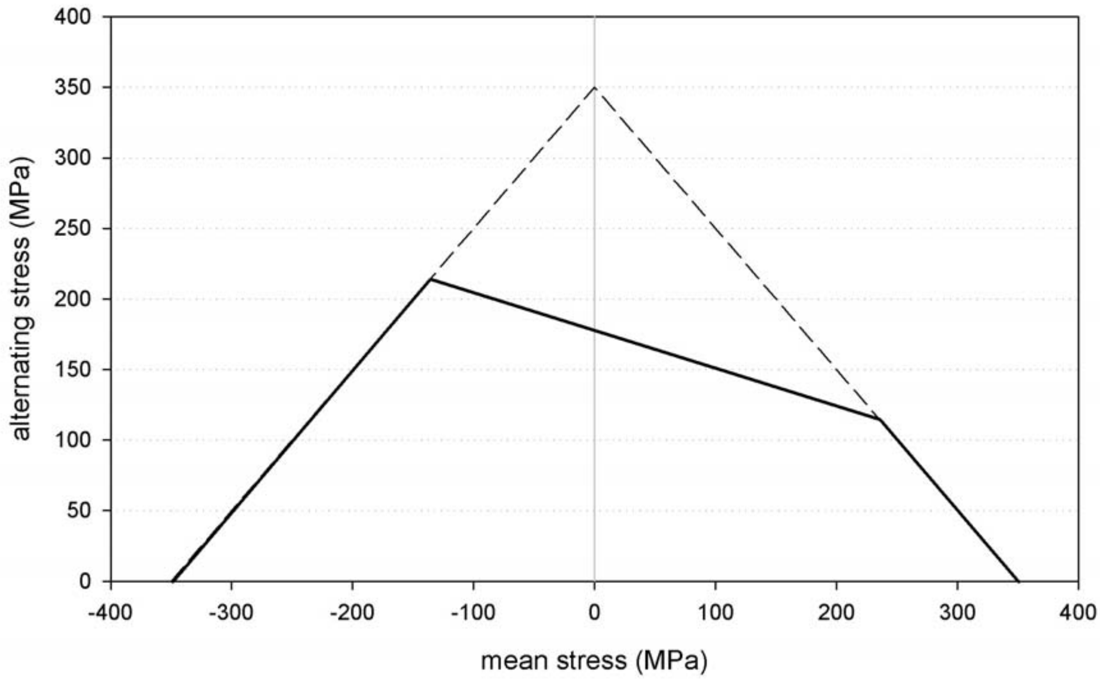


Figure 9. Schematic of the Société Nationale des Chemins de Fer (MGD)

3. TEST RESULTS AND DISCUSSION

3.1 Material Characterization Results

The following section provides tabular and graphical results of the tensile and chemical composition testing. Also in this section the most notable characteristics of the material property data for the tested Class B wheel steel are described and contrasted to the data given in the AAR specification for carbon steel wheels [8]. The tensile and chemical test result summaries are extracted from the actual data tabulated in Appendix A – Chemical Composition Analysis Results. Additional details regarding the specifics of all the tensile tests are included in Appendix A.

A summary of the chemical composition data is shown in Table 2, with the AAR specification allowables provided for comparison. The results indicate that both railroad wheel samples contained the required elements within the specified range, below the maximum, or above the minimum given for the Class B wheel steel, as specified in Section 8.1 of AAR Specifications M-107/208 [8].

Table 2. Chemical Analysis Results for the Class B Wheel Steel

Sample ID	Element (Weight Percent)				
	C	Mn	P	S	Si
0	0.64	0.83	0.02	0.03	0.23
1	0.64	0.76	0.02	0.03	0.28
Minimum [8]	0.57	0.60			0.15
Maximum [8]	0.67	0.85	0.05	0.05	

Tensile test results for each of the three temperatures are shown in Table 3, with the room temperature baseline tensile data for Class B wheel steel [1] also included for comparison. Room temperature tensile yield stress (σ_{YS}) exceeded the minimum given by the AAR baseline, with the ultimate tensile strength (σ_{UTS}) also within the range specified.

Two observations are apparent from the test data given in Table 3. First, a dramatic decrease in the ultimate tensile strength and yield stress occurred when testing at a temperature of 1000°F, with a greater than 50 percent reduction in σ_{UTS} and 35 percent reduction in σ_{YS} as compared to the room temperature and 500°F tests. Second, a decrease in the reduction in area for all 500°F tests, compared to both room temperature and 1000°F tests was observed. The actual tensile specimens were randomly selected for testing at the three temperatures, with each three-specimen group combined to include at least one specimen from each wheel, as previously shown in Figure 3. Therefore, it is unlikely that the difference in reduction of area, for the three temperature levels, is a consequence of material variation in one specific wheel. However, it is not unusual for materials to exhibit a non-linear ductility response as a function of temperature.

Table 3. Tensile Tests Results for the Class B Wheel Steel at Room and Elevated Temperature

Temp (°F)	Specimen ID	σ_{UTS}, ksi	σ_{YS}, ksi	ε, %	RA, %
R.T.	1	164.6	112.9	12.0	26.0
	3	158.9	106.3	13.0	29.4
	8	157.1	104.6	13.0	31.4
	Average →	**160.2**	**107.9**	**12.7**	**28.9**
	Class B baseline [1]	**130-170**	**80**		
500	2	165.0	102.3	11.0	14.5
	4	166.6	110.9	10.0	16.2
	9	162.2	104.1	11.0	15.9
	Average →	**164.6**	**105.8**	**10.7**	**15.5**
1000	5	80.3	68.1	9.0	24.1
	6	78.7	69.8	12.0	35.1
	7	75.7	65.9	16.0	44.7
	Average →	**78.2**	**67.9**	**12.3**	**34.6**

3.2 Fatigue Test Results

A total of 123 constant amplitude fatigue tests were performed at the three different test temperatures.

A summary of all fatigue tests performed at room temperature, 500°F, and 1000°F is given in Tables 4 to 6, respectively. Data is presented in terms of R-ratio, maximum stress, cycles to failure, and where possible the orientation of the initiation site (high temperature). The orientation of the initiation site was measured relative to the position of the thermocouple, with 0° being the position in which the thermocouple is in contact with the fatigue specimen. It is worthwhile to note that the maximum stress given in Tables 4 to 6 is not the stress at which the specimens were tested. Due to the specimen's hourglass geometry a stress concentration is produced in the specimen. Therefore, the effective test stress is calculated simply as:

$$\Delta\sigma = K_t \Delta S = K_t \, {}^{\Delta P}\!/_{A} \quad (7)$$

where $\Delta\sigma$ = effective applied stress range
K_t = stress concentration due to hourglass geometry = 1.05
ΔS = minimum diameter specimen section stress range
ΔP = load range applied to specimen

A = minimum diameter specimen area

A summary graph for all fatigue tests at each of the three temperatures and four R-ratios is shown in Figure 10. To better highlight the differences at each of the three temperatures, graphical summaries of the fatigue data for room temperature, 500°F, and 1000°F are provided in Figures 11 to 13, respectively. For each graph, cycles to failure are given as a function of actual stress range, which includes the stress concentration effect (K_t = 1.05). As expected, a certain degree of scatter in fatigue results is shown for each particular stress range, with the highest amount of scatter at the lower stress levels and therefore the higher life regime.

Also provided on each of the summary plots are regression curve fits for the data at the lower R-ratios of R = -1.0 and 0.05. Due to the limited amount of testing at the higher R-ratios of R = 0.5 and 0.7, only the fatigue life at the 10^7 life regime, termed the endurance limit, was obtained. To obtain the curves shown in Figures 11 to 13, a simple linear regression on the fatigue data, up to and including the 10^6 life regime, was performed. In this case the independent and dependent variables were N and ΔS, respectively. A horizontal line, corresponding to an average stress level for all runout data, was then extended out to the 10^7 life regime. It is interesting to note that for the 1000°F high-temperature tests, there did not appear to be the usual endurance limit transition at the lower stress levels, for each R-ratio, as was found with the room temperature and 500°F tests.

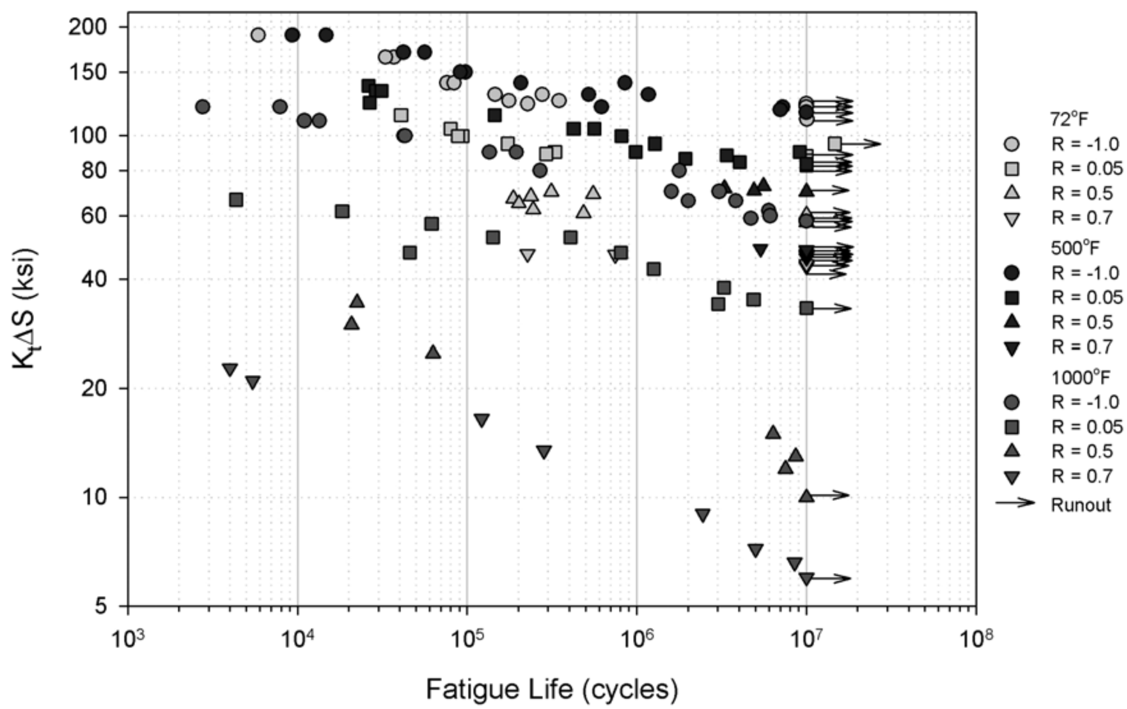


Figure 10. Summary of All Fatigue Tests Performed During Test Program

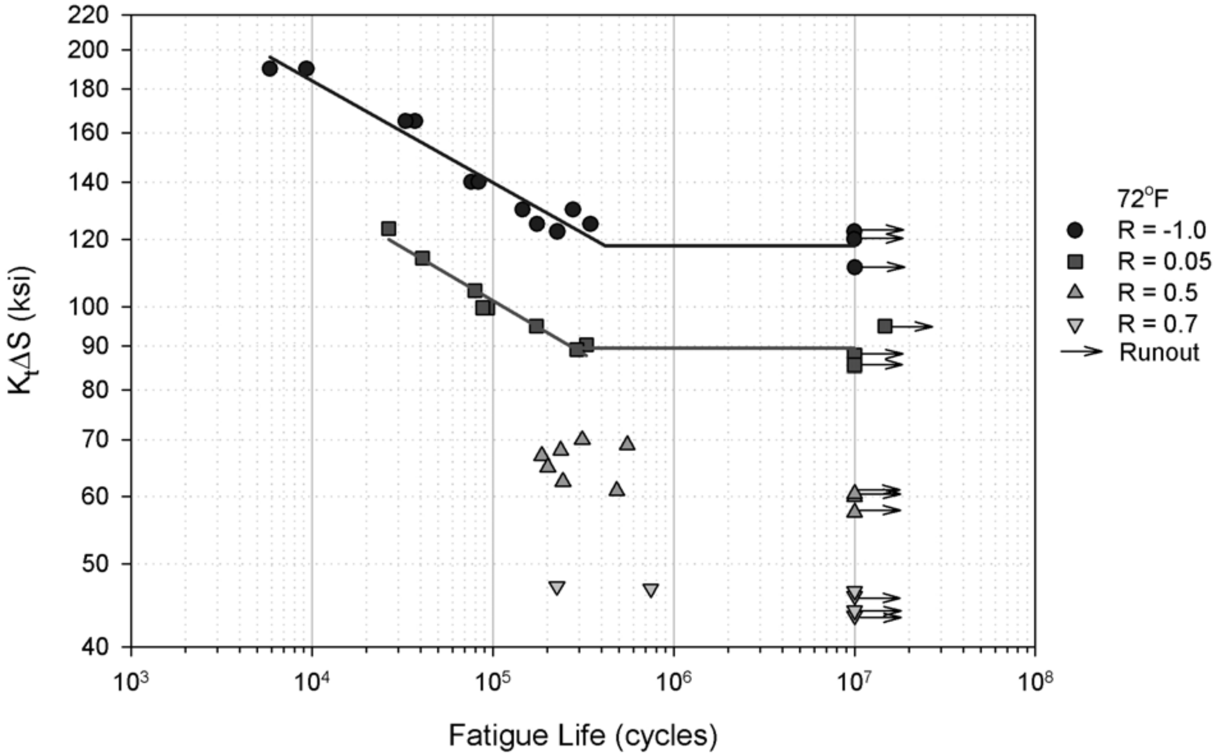


Figure 11. Fatigue Test Results at Room Temperature for the Class B Wheel Steel

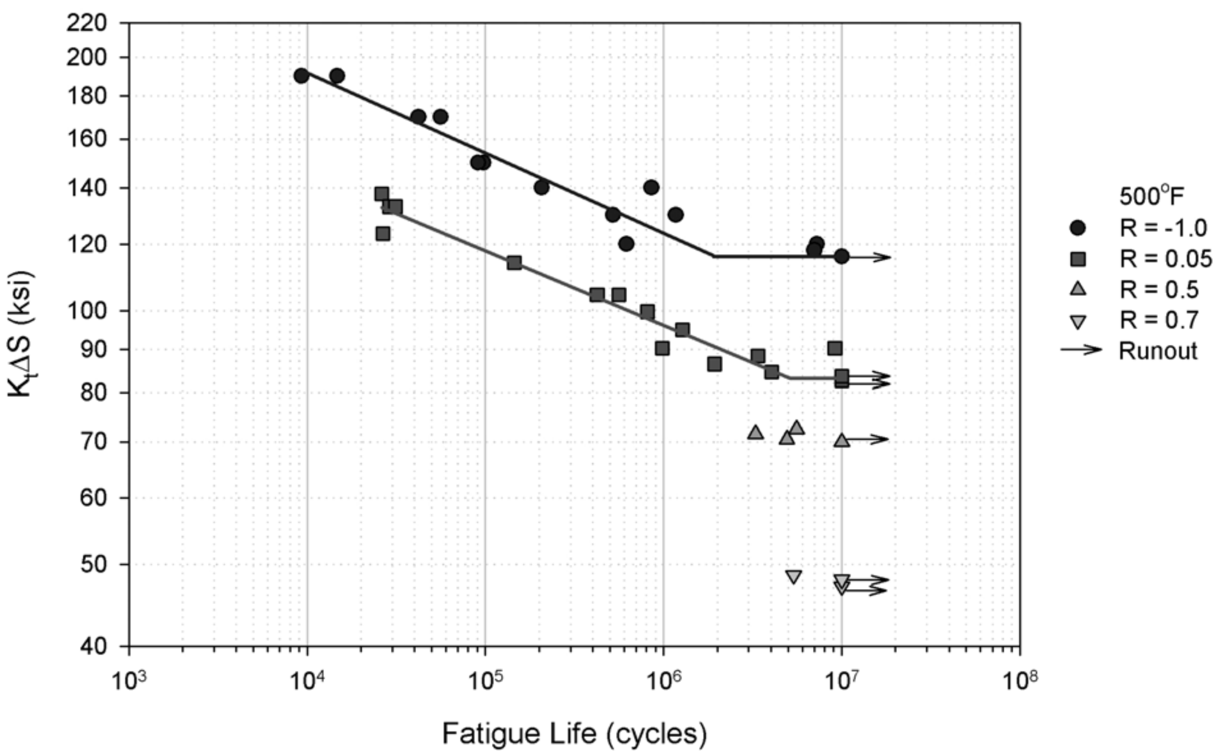


Figure 12. Fatigue Test Results at 500°F for the Class B Wheel Steel

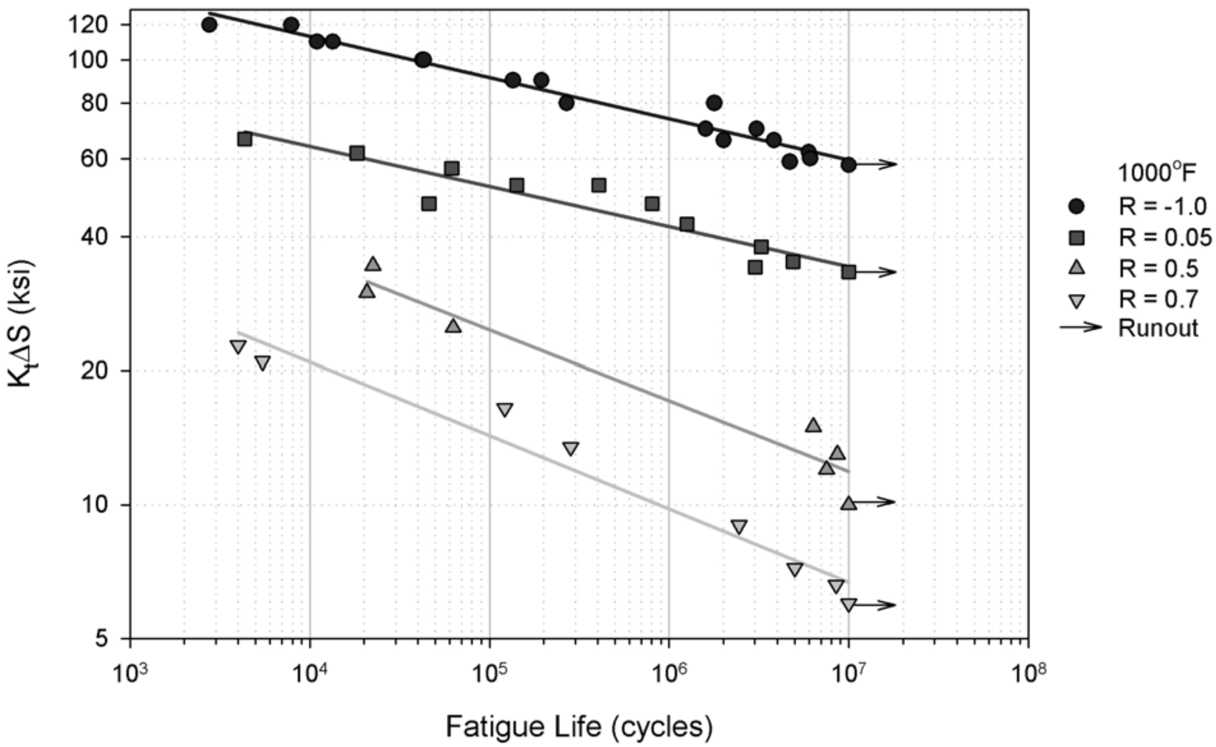


Figure 13. Fatigue Test Results at 1000°F for the Class B Wheel Steel

Power law functions for each of the regression fits shown in Figures 11 to 13 are given in Table 7, with cycles given as a function of stress range.

Due to the large amount of data produced in this fatigue test program, over a wide variety of R-ratios, it is possible to develop the endurance limit diagram for the three test temperatures. Endurance limit diagrams for the room temperature, 500°F, and 1000°F tests are shown together for comparison in Figure 14. Due to the similarity of tensile and fatigue test results for the room temperature and 500°F tests, it is not unexpected to see similar endurance limit diagrams for these two temperatures. Also, the vast difference in tensile strength properties when testing at 1000°F is indicative of the subsequent detrimental effect on the endurance limit diagram.

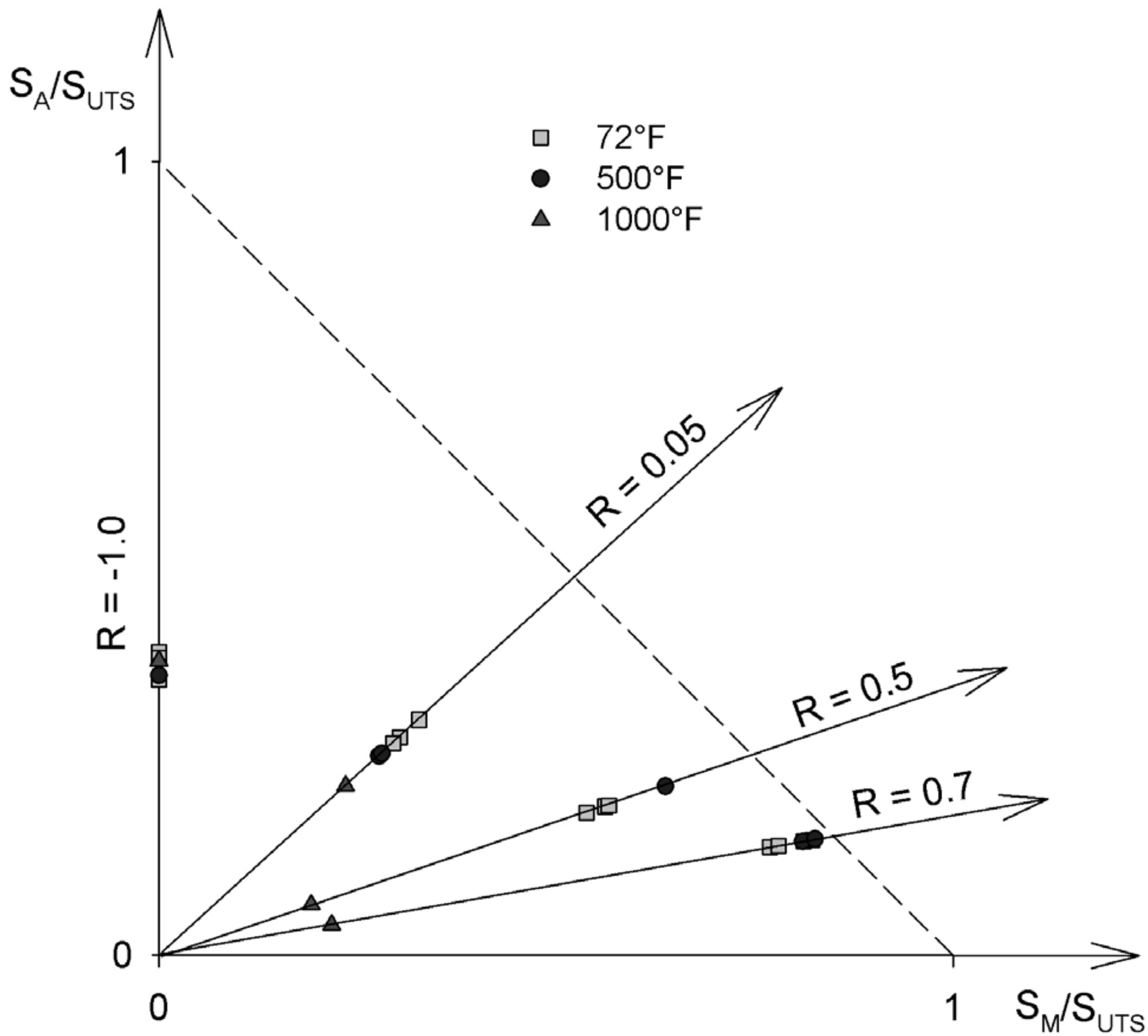
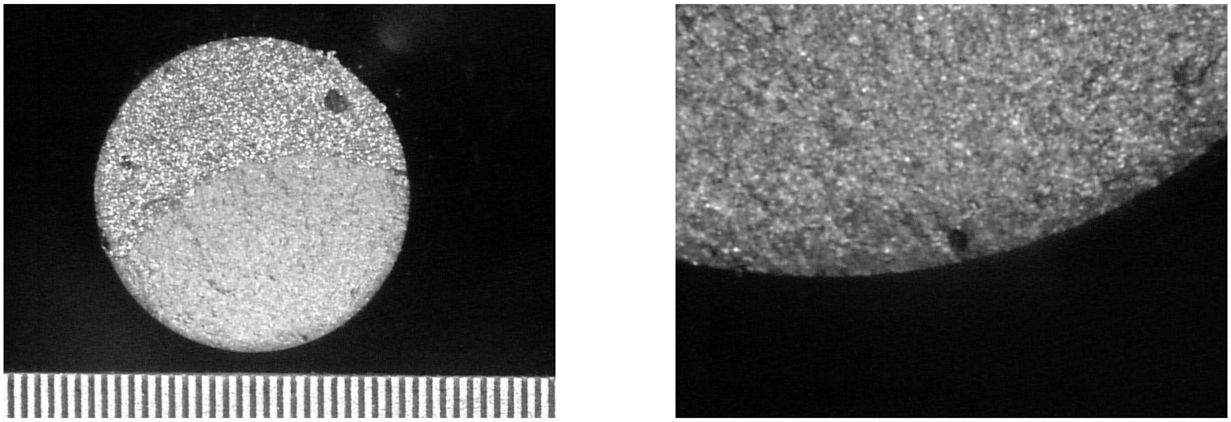
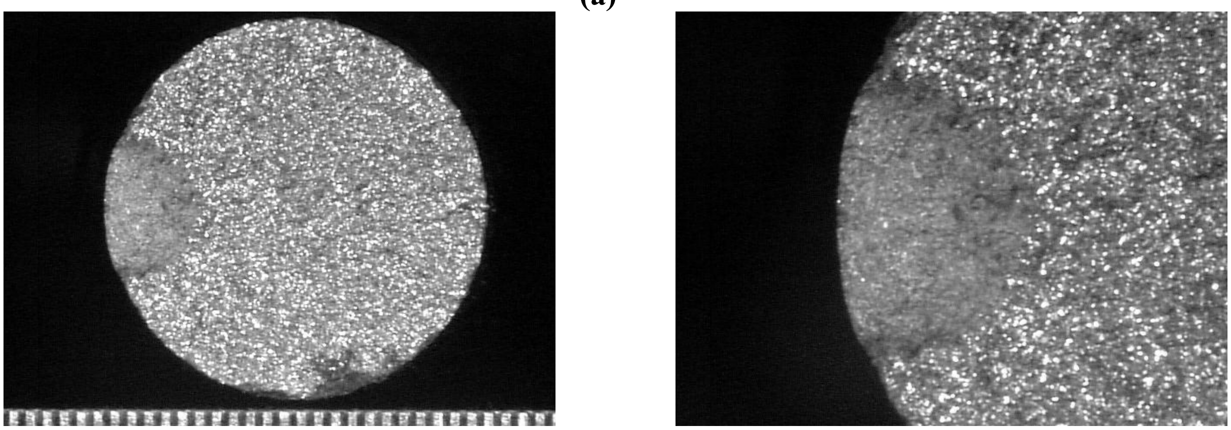


Figure 14. Endurance Limit Diagram for the Three Test Temperatures

Photographs of typical fracture surfaces for the room temperature, 500°F, and 1000°F tests are shown in Figures 15 to 17, respectively. It is interesting to note that both surface and sub-surface initiation sites were observed for all test temperatures. Also as previously given in Tables 3 to 5 there appeared to be no preferential initiation site at the point where the thermocouple was in contact with the specimen during high-temperature testing.



(a)



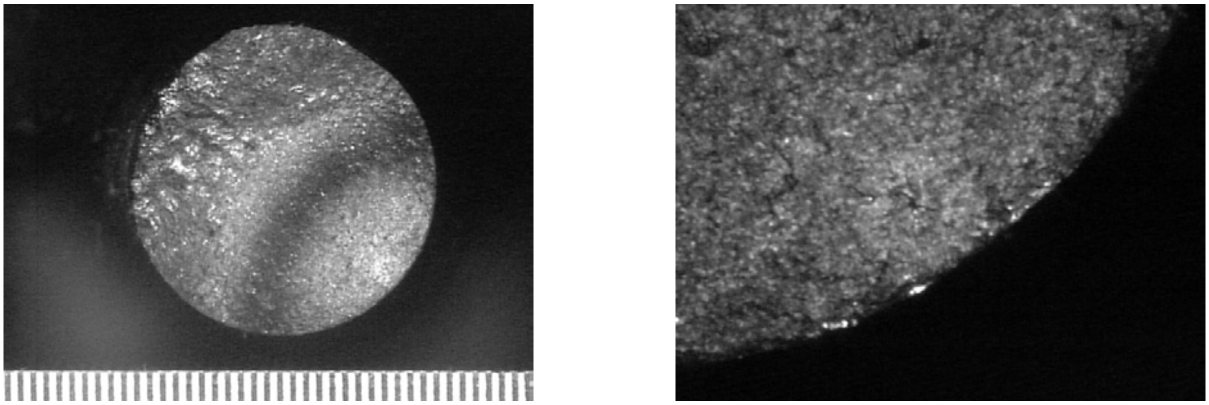
(b)

Figure 15. Representative Photographs of Room Temperature Fatigue Specimens (a) R = -1.0, and (b) R = 0.7 (scale division = 0.01 inch)

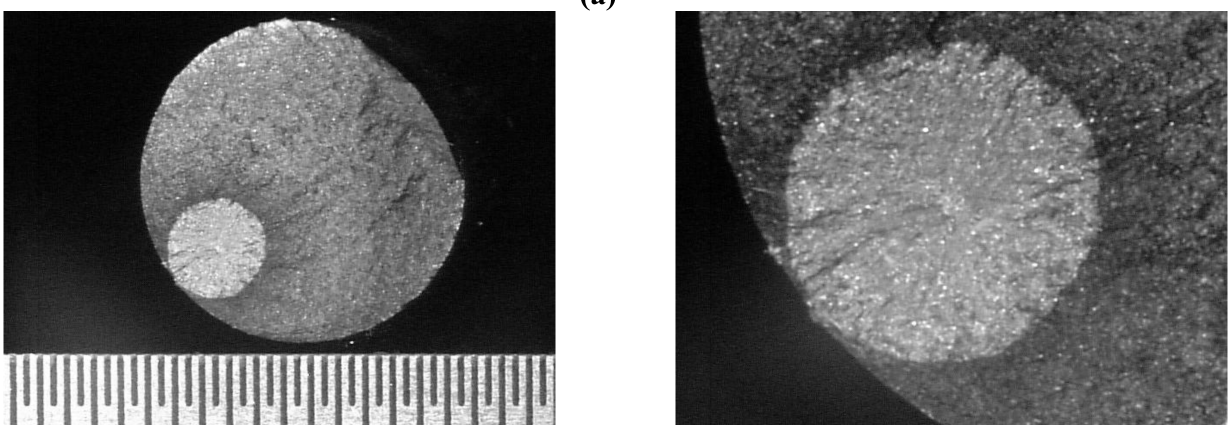
3.3 Estimation of Sines Parameters

Based on the results given in the previous section it is possible to provide an estimation of the Sines parameters, A and α, for the 10^7 life regime. Endurance limit data at the 10^7 life regime, for R-ratios = -1.0 and 0.05, is required to calculate the two material constants (see Section 2.3.1). The data used to calculate the Sines parameters are shown in Figure 18 for each of the three temperatures. Using Eq. 3 and 5 the constants A and α were estimated with results provided in Table 8.

Very similar Sines parameters were calculated for the room temperature and 500°F fatigue tests. However, the Sines parameters for the 1000°F fatigue tests are dramatically different from those of the lower temperature fatigue tests. This is not surprising considering the large difference in both tensile and fatigue properties obtained for the 1000°F tests, when compared to the room temperature and 500°F tests.



(a)



(b)

Figure 16. Representative Photographs of 500°F Fatigue Specimens (a) R = -1.0, and (b) R = 0.05 (scale division = 0.01 inch)

Table 4. Summary of the Fatigue Tests Performed at Room Temperature for the Class B Wheel Steel

R-ratio	Specimen ID	Maximum Stress[1] (ksi)	Cycles to failure[2]
-1	1E-7	95	5,887
	1E-5	95	9,372
	0A-5	82.5	33,054
	0D-10	82.5	37,195
	0H-4	75	76,307
	1D-2	70	83,843
	0B-6	65	146,448
	0A-4	65	278,532
	1H-10	62.5	176,207
	1H-8	62.5	347,771
	0B-2	61.25	227,727
	0A-6	61.25	>10,000,000
	0C-5	60	>10,000,000
	0H-9	60	>10,051,271
0.05	1F-1	130	26,589
	0A-9	120	40,740
	1B-8	110	79,808
	0E-8	105	88,296
	0G-3	105	93,800
	0A-7	100	174,161
	1A-10	100	>14,713,625
	0H-3	95	329,472
	0A-3	93.75	292,027
	1H-4	92.5	>10,000,000
	0G-7	90	>10,000,000
0.5	0D-6	140	312,699
	0C-3	138	553,734
	0E-4	136	237,932
	0D-5	134	187,006
	1H-9	130	201,557
	0C-9	125	244,378
	0H-8	122	486,206
	1B-10	121	>10,000,000
	1B-1	120	>10,000,000
	1H-1	115	>10,000,000
0.7	0C-2	157	226,632
	0E-5	156	747,274
	1B-5	155	>10,000,000
	0E-3	153	>10,000,000
	0G-5	147	>10,000,000
	1F-2	145	>10,000,000

[1] Maximum stress = test stress x specimen K_t (1.05)
[2] Runout = 10,000,000 cycles

Table 5. Summary of the Fatigue Tests Performed at 500°F for the Class B Wheel Steel

R-ratio	Specimen ID	Maximum Stress[1] (ksi)	Cycles to failure[2]	Orientation of Initiation Site (°)
-1	0D-7	95	9,320	270
	1B-7	95	14,769	300
	1B-4	85	42,118	0
	1A-5	85	56,349	270
	1A-4	75	91,475	270
	1D-3	75	97,623	
	1F-5	70	207,115	135
	0B-8	70	853,650	180
	1D-8	65	521,767	
	1A-6	65	1,174,896	300
	1D-4	60	620,522	
	1E-6	60	7,247,943	135
	0E-6	58	>10,000,000	
	1E-9	59	7,014,039	270
0.05	1D-10	145	26,233	
	0C-6	140	28,955	
	0B-10	140	31,365	330
	0D-3	130	26,575	225
	1F-8	120	145,780	300
	0D-2	110	423,980	300
	0C-8	110	562,619	90
	0E-9	105	810,829	270
	0G-4	100	1,275,912	0
	1B-2	95	983,955	
	0H-1	95	9,150,149	345
	1F-4	93	3,388,655	180
	1F-3	91	1,930,844	180
	1B-6	89	4,029,751	180
	0C-10	88	>10,000,000	
	0A-10	87	>10,000,000	
0.5	0A-1	145	5,570,502	30
	0D-9	143	3,286,854	345
	1F-7	141	4,912,155	
	0G-9	140	>10,000,000	
0.7	1H-2	162	5,355,081	
	0D-1	161	>10,000,000	
	1F-9	160	>10,000,000	
	0G-10	157	>10,000,000	

[1] Maximum stress = test stress x specimen K_t (1.05)
[2] Runout = 10,000,000 cycles

Table 6. Summary of the Fatigue Tests Performed at 1000°F for the Class B Wheel Steel

R-ratio	Specimen ID	Maximum Stress[1] (ksi)	Cycles to failure[2]	Orientation of Initiation Site (°)
-1	1E-3	60	2,770	45
	1A-1	60	7,913	45
	1A-8	55	10,971	90
	0E-7	55	13,468	45
	0H-2	50	42,520	45
	0G-6	50	43,217	90
	1A-2	45	135,222	90
	1D-7	45	195,352	110
	0E-1	40	269,339	0
	0H-6	40	1,784,742	80
	1H-6	35	1,599,652	330
	0B-4	35	3,068,724	80
	0E-2	33	2,010,031	45
	1D-5	33	3,838,683	210
	1E-8	31	5,994,347	180
	1B-9	30	6,118,901	180
	1A-7	29.5	4,707,372	330
	1H-7	29	>10,000,000	
0.05	0A-8	70	4,338	45
	1A-9	65	18,357	45
	0B-9	60	61,736	
	1A-3	55	142,017	
	1D-6	55	405,961	
	1B-3	50	46,109	
	1F-6	50	804,980	
	0A-2	45	1,260,330	45
	1E-1	40	3,254,394	
	1D-1	37	4,876,691	
	0B-7	36	3,026,588	180
	0C-4	35	>10,000,000	
0.5	0H-7	69	22,425	180
	0G-2	60	20,854	
	1E-4	50	62,929	
	0B-3	30	6,349,757	
	0B-5	24	7,531,811	
	0E-10	20	>10,000,000	
0.7	0B-1	76	4,005	
	0G-1	70	5,447	
	1H-3	55	121,785	
	0C-1	45	282,593	
	1E-2	30	2,445,403	
	1D-9	26	8,657,319	
	1H-5	24	5,007,242	
	0C-7	22	8,494,894	
	0D-4	20	>10,000,000	

[1] Maximum stress = test stress x specimen K_t (1.05)
[2] Runout = 10,000,000 cycles

Table 7. Regression Analysis of Fatigue Data for Each of the Three Test Temperatures

Temp (°F)	R-ratio	Stress Range, ΔS (ksi)	Power Law Constants		Cycles to Failure[1]
			A	b	
R.T.	-1.0	> 117.9	1.409×10^{22}	-7.994	$N = A\Delta S^{b}$
		≤ 117.9			Runout
	0.05	> 89.5	3.810×10^{20}	-7.761	$N = A\Delta S^{b}$
		≤ 89.5			Runout
500	-1.0	> 116.0	1.166×10^{26}	-9.625	$N = A\Delta S^{b}$
		≤ 116.0			Runout
	0.05	> 83.1	2.191×10^{27}	-10.777	$N = A\Delta S^{b}$
		≤ 83.1			Runout
1000	-1.0	≥ 58.0	2.052×10^{25}	-10.350	$N = A\Delta S^{b}$
	0.05	≥ 33.3	6.543×10^{21}	-9.763	$N = A\Delta S^{b}$
	0.5	≥ 10.0	2.143×10^{13}	-5.947	$N = A\Delta S^{b}$
	0.7	≥ 6.0	5.753×10^{11}	-5.830	$N = A\Delta S^{b}$

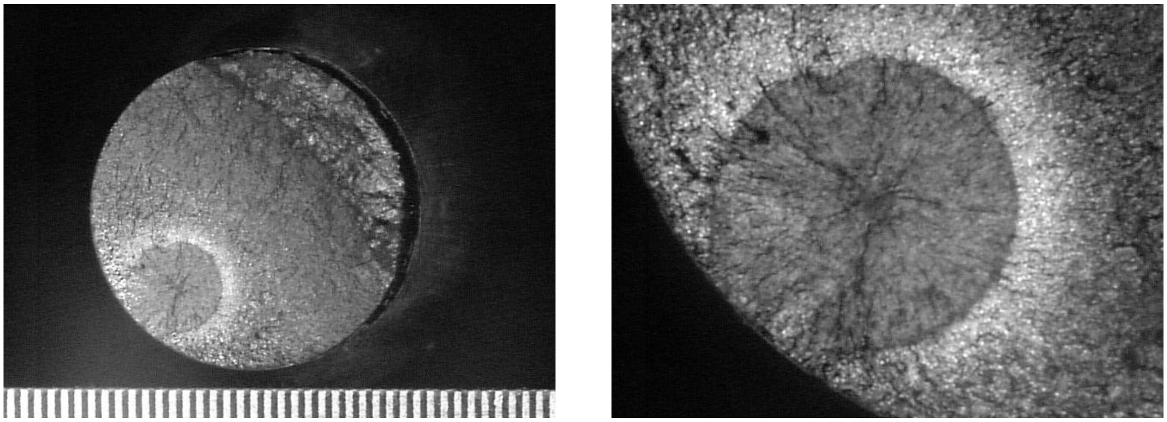
[1] To calculate stress range: $\Delta S = A^{-1/b} N^{1/b}$

Table 8. Sines Criterion Material Constant Estimates for the Three Test Temperatures

Temp (°F)	R-ratio	Sines Constants at Endurance Limit (10^7 Life Regime)			
		Stress Amplitude (ksi)		A (ksi)[1]	α[2]
		f_1	f_1'		
R.T.	-1.0	59.0		27.8	0.149
	0.05		44.8		
500	-1.0	58.0		27.3	0.186
	0.05		41.6		
1000	-1.0	29.0		13.7	0.347
	0.05		16.7		

[1] $A = \frac{\sqrt{2}}{3} f_1$

[2] $\alpha = \frac{\sqrt{2}}{3}\left(\frac{f_1}{f_1'} - 1\right)$



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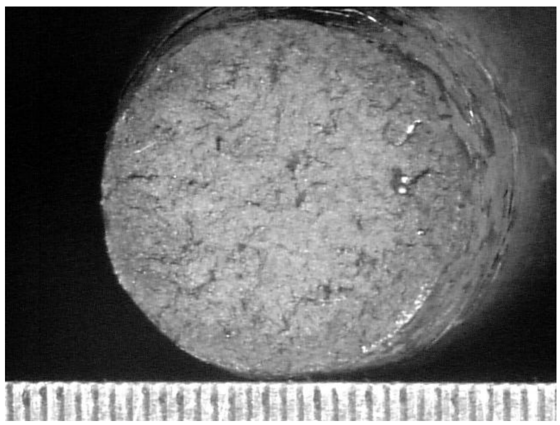

(b)

Figure 17. Representative Photographs of 1000°F Fatigue Specimens (a) R = -1.0, and (b) R = 0.5 (scale division = 0.01 inch)

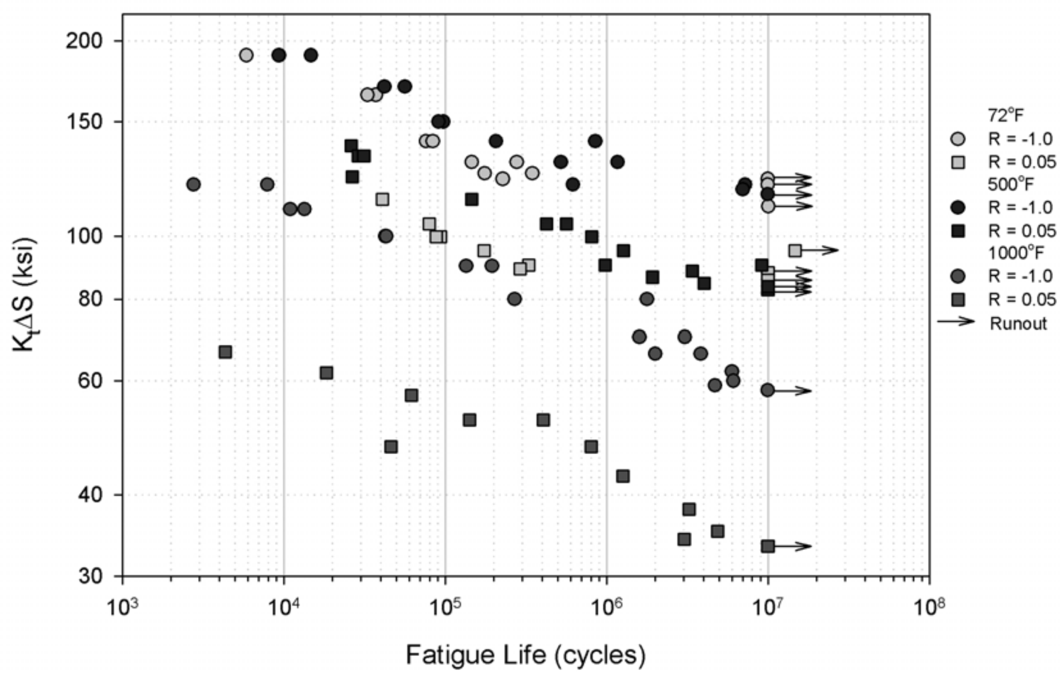

Figure 18. Fatigue Test Results Used in the Estimation of the Sines Criterion Material Constants

4. SUMMARY

The material property evaluations described herein provide an assessment of the chemical, tensile, and fatigue behavior observed for the Class B wheel steel material. Fatigue testing was performed to determine the S-N curves for each of the three temperatures, 72°F, 500°F, and 1000°F. Furthermore, a large number of fatigue tests were performed at R-ratios of -1.0 and 0.05 for each of the test temperatures to enable reliable estimates of the Sines parameters, A and α. Chemical, tensile, and fatigue results can be briefly summarized with major conclusions indicated below.

1. Two chemical analysis tests and nine tensile tests were undertaken to characterize the Class B railroad wheel steel material. Individual sections from each of the two railroad wheels were selected to enable a material characterization test sampling of both wheels.

2. Chemical composition analysis indicated that both wheel samples were within the range for a Class B railroad wheel, as given in AAR specification M-107/208 [8].

3. Monotonic tensile tests were undertaken for the Class B wheel steel, at room temperature, 500°F, and 1000°F. Room temperature test results were found to be in accordance with AAR baseline values, as given in AAR Standard S-660-83 [1].

4. Very similar ultimate tensile strength and yield stress results were found for the room temperature and 500°F tests. However, a greater than 50 percent reduction in ultimate tensile strength and 35 percent reduction in yield stress was observed for the 1000°F tensile tests, when compared to both the room temperature and 500°F tests.

5. A large decrease in the reduction in area for all 500°F tests, compared to both room temperature and 1000°F tests, was observed. As the tensile specimens were randomly selected from both railroad wheels, for each of the three temperatures, it is unlikely that the difference is a consequence of material variation in one specific wheel.

6. A total of 123 constant amplitude fatigue tests were completed at the three test temperatures. The vast majority of testing (70%) was performed at R-ratios of -1.0 and 0.05 to enable the S-N curves to be developed. The remainder of testing was undertaken to obtain the endurance limit at 10^7 cycles for R-ratios of 0.5 and 0.7.

7. The degree of scatter for fatigue tests averaged approximately one order of magnitude (10x) for all tests performed at replicate stress levels, with a scatter range of between 1.02x – 84.5x. As expected, greater levels of scatter and less repeatability were apparent at the lower stress levels.

8. Fracture surfaces indicated both surface and sub-surface initiation sites under all test temperatures. The thermocouple position during high-temperature testing did not appear to provide a preferential initiation site.

9. Endurance limit data was obtained for all R-ratios at each of the three test temperatures. However, for the 1000°F tests there did not appear to be the usual endurance limit transition at the lower stress levels, as was found with the room temperature and 500°F tests. Endurance limit diagrams for the three test temperatures were constructed.

10. Based on the endurance limit data for R-ratios of -1.0 and 0.05, an estimation of the Sines parameters, A and α, was obtained for each of the three test temperatures. Similar parameters were calculated for the room temperature and 500°F fatigue tests, with significantly different parameters obtained for the 1000°F fatigue tests.

5. REFERENCES

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[6] Sines, G., *Behavior of Metals Under Complex Static and Alternating Stresses*, *Metal Fatigue*, G. Sines and J. L. Waisman, Eds., New York: McGraw-Hill, pp.145-169, 1959.

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[8] Association of American Railroads, Specification M-107-84 and M-208-84, *Wheels, Carbon Steel*, Manual of Standards and Recommended Practices, Section G, Wheels and Axles, 1984.

Appendix A – Chemical Composition Analysis Results

CONAM KAWIN

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TEST REPORT

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FRASER J. MCMASTER

P.O. # 50138

DESCR TWO SAMPLES (LABELLED O & F)
-

REPORT DATE: 10/17/2001

LAB NO: 1001-015 / 01 JOB NO: 10/03 #V19

CHEMISTRY BLOCK #O

CHEMICAL ANALYSIS

Si	.23	Mn	.83	C	.64
P	.020	S	.031		

TEST METHODS: ASTM E 1019 ; ASTM E 415 ;

QA INSPECTOR

ALL CHEMICAL TEST RESULTS ARE REPORTED IN WEIGHT PERCENT UNLESS OTHERWISE NOTED.

PAGE 1 OF 11

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TEST REPORT

SOUTHWEST RESEARCH INST. 7010
6220 CULEBRA RD
P. O. DRAWER 28510
SAN ANTONIO TX 78284
FRASER J. MCMASTER

P. O. # 50138

DESCR TWO SAMPLES (LABELLED O & F)
-

REPORT DATE: 10/17/2001

LAB NO: 1001-015 / 02

JOB NO: 10/03 #V18

CHEMISTRY BLOCK #1

CHEMICAL ANALYSIS

Si	.24	Mn	.84	C	.66
P	.019	S	.021		

TEST METHODS: ASTM E 1019 ; ASTM E 415 ;

QA INSPECTOR

ALL CHEMICAL TEST RESULTS ARE REPORTED IN WEIGHT PERCENT UNLESS OTHERWISE NOTED.

PAGE 2 OF 11

Appendix B – Tensile Test Results

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DESCR TWO SAMPLES (LABELLED O & F)
-

REPORT DATE: 10/17/2001

LAB NO: 1001-015 / 03

JOB NO:

ROOM TEMPERATURE SPECIMEN #1

MECHANICAL TESTING RESULTS

DIAMETER:	.250	AREA:	.0491
YIELD STRENGTH: lbs	5,543.	YIELD STRENGTH psi :	112,921
ULT STRENGTH: lbs	8,081.	TENSILE psi :	164,624
ELONG ON 1.00 IN. :	.12	ELONGATION % :	12.00
		REDUCTION OF AREA % :	26.04

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM A 370 ;

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PAGE 3 OF 11

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P.O. # 50138

DESCR TWO SAMPLES (LABELLED O & F)
-

REPORT DATE: 10/17/2001

LAB NO: 1001-015 / 04 JOB NO:

ROOM TEMPERATURE SPECIMEN #3

MECHANICAL TESTING RESULTS

DIAMETER:	.250	AREA:	.0491
YIELD STRENGTH: lbs	5,220.	YIELD STRENGTH psi :	106,341
ULT STRENGTH: lbs	7,802.	TENSILE psi :	158,941
ELONG ON 1.00 IN. :	.13	ELONGATION % :	13.00
		REDUCTION OF AREA % :	29.44

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM A 370 ;

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DESCR TWO SAMPLES (LABELLED O & F)
-

REPORT DATE: 10/17/2001

LAB NO: 1001-015 / 05 JOB NO:

ROOM TEMPERATURE SPECIMEN #8

MECHANICAL TESTING RESULTS

DIAMETER:	.245	AREA:	.0471
YIELD STRENGTH: lbs	4,932.	YIELD STRENGTH psi :	104,616
ULT STRENGTH: lbs	7,406.	TENSILE psi :	157,094
ELONG ON 1.00 IN. :	.13	ELONGATION % :	13.00
		REDUCTION OF AREA % :	31.35

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM A 370 ;

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DESCR TWO SAMPLES (LABELLED O & F)
-

REPORT DATE: 10/17/2001

LAB NO: 1001-015 / 06

JOB NO:

500 DEG F SPECIMEN #2

MECHANICAL TESTING RESULTS

DIAMETER:	.252	AREA:	.0499
YIELD STRENGTH: lbs	5,100.	YIELD STRENGTH psi :	102,254
ULT STRENGTH: lbs	8,229.	TENSILE psi :	164,989
ELONG ON 1.00 IN. :	.11	ELONGATION % :	11.00
		REDUCTION OF AREA % :	14.51

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM E 21 ;

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PAGE 6 OF 11

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DESCR TWO SAMPLES (LABELLED D & F)
-

REPORT DATE: 10/17/2001

LAB NO: 1001-015 / 07 JOB NO:

500 DEG F SPECIMEN #4

MECHANICAL TESTING RESULTS

DIAMETER:	.249	AREA:	.0487
YIELD STRENGTH: lbs	5,400.	YIELD STRENGTH psi :	110,893
ULT STRENGTH: lbs	8,115.	TENSILE psi :	166,648
ELONG ON 1.00 IN. :	.10	ELONGATION % :	10.00
		REDUCTION OF AREA % :	16.16

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM A 370 ;

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PAGE 7 OF 11

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DESCR TWO SAMPLES (LABELLED O & F)
-

REPORT DATE: 10/17/2001

LAB NO: 1001-015 / 08

JOB NO:

500 DEG F SPECIMEN #8

MECHANICAL TESTING RESULTS

DIAMETER:	.253	AREA:	.0503
YIELD STRENGTH: lbs	5,232.	YIELD STRENGTH psi :	104,072
ULT STRENGTH: lbs	8,153.	TENSILE psi :	162,176
ELONG ON 1.00 IN. :	.11	ELONGATION % :	11.00
		REDUCTION OF AREA % :	15.91

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM A 370 ;

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DESCR TWO SAMPLES (LABELLED D & F)
-

REPORT DATE: 10/17/2001

LAB NO: 1001-015 / 09

JOB NO:

1000 DEG F SPECIMEN #5

MECHANICAL TESTING RESULTS

DIAMETER:	.248	AREA:	.0483
YIELD STRENGTH: lbs	3,288.	YIELD STRENGTH psi :	68,067
ULT STRENGTH: lbs	3,880.	TENSILE psi :	80,323
ELONG ON 1.00 IN. :	.09	ELONGATION % :	9.00
		REDUCTION OF AREA % :	24.14

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM E 21 ;

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PAGE 9 OF 11

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DESCR TWO SAMPLES (LABELLED O & F)
-

REPORT DATE: 10/17/2001

LAB NO: 1001-015 / 10 JOB NO:

1000 DEG F SPECIMEN #6

MECHANICAL TESTING RESULTS

DIAMETER:	.252	AREA:	.0499
YIELD STRENGTH: lbs	3,480.	YIELD STRENGTH psi :	69,773
ULT STRENGTH: lbs	3,923.	TENSILE psi :	78,655
ELONG ON 1.00 IN. :	.12	ELONGATION % :	12.00
		REDUCTION OF AREA % :	35.11

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM E 21 ;

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PAGE 10 OF 11

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DESCR TWO SAMPLES (LABELLED O & F)
–

REPORT DATE: 10/17/2001

LAB NO: 1001-015 / 11 JOB NO:

1000 DEG F SPECIMEN #7

MECHANICAL TESTING RESULTS

DIAMETER:	.246	AREA:	.0475
YIELD STRENGTH: lbs	3,132.	YIELD STRENGTH psi :	65,896
ULT STRENGTH: lbs	3,596.	TENSILE psi :	75,659
ELONG ON 1.00 IN. :	.16	ELONGATION % :	16.00
		REDUCTION OF AREA % :	44.66

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM E 21 ;

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PAGE 11 OF 11