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MULTIAXIAL FATIGUE OF A RAILWAY WHEEL STEEL

CHIN-SUNG CHUNG[1], HO-KYUNG KIM[2,*]

[1]R&D Center, Flow Master Co. Seoul, Korea, 150-105
[2]Dept. of Automotive Engineering,
Seoul National University of Science and Technology, Korea
*Corresponding Author: kimhk@seoultech.ac.kr

Abstract

Uniaxial and biaxial torsional fatigue specimens were extracted from a railway wheel steel. The fatigue tests were performed with the stress ratio of R= -1 by using uniaxial and biaxial torsional fatigue test specimens at room temperature in air. The ultimate and yield strengths of the steel were evaluated. The uniaxial fatigue limit was 422.5 MPa, which corresponds to 67% of the ultimate tensile strength. The ratio of τ_e/σ_e was 0.63. Appropriate parameters to predict the fatigue life of the steel under multiaxial stress states were reviewed.

Keywords: Fatigue strength, Multiaxial fatigue, Railway wheel steel, SWT fatigue parameter.

1. Introduction

Railway wheels are subjected to mechanical and thermal loads, and as train speeds and weights are increased, these loads increase. With the increase of train speeds and axle loads, rolling contact fatigue of railway wheels has become an important issue with respect to failure. Minor fatigue damage in the wheel can reduce the ride comfort and increase the maintain cost for a vehicle. It also increases the vehicle–track interaction forces, resulting in potential for derailment and reduction of the integrity of the vehicle. Therefore, it is highly important to evaluate the fatigue properties of the wheel steel.

Studies on the fatigue strength of wheels have also been limited [1-4]. For instance, Bernasconi et al. [1] used specimens of uniaxial and biaxial torsional fatigue taken from the rim of wheel steel to evaluate the multiaxial fatigue strength of the wheel steel under combined out-of-phase alternating torsion and pulsating compressive axial loads which is similar to that observed under the

Nomenclatures

E	Elastic modulus
Elong.	Elongation
FP	Smith-Watson-Topper multiaxial fatigue parameter
G	Shear modulus
N_f	Fatigue lifetime
YS	Yield strength
UTS	Ultimate tensile strength

Greek Symbols

ε_f	True fracture strain
ε_1	Maximum principal strain
ε_3	Minimum principal strain
$\Delta\varepsilon$	Difference between the maximum and minimum normal strain
σ_e	Uniaxial fatigue limit
σ_{eq}	Von Mises equivalent stress
σ_{max}	Maximum stress on the maximum principal strain plane
σ_1	Maximum principal stress
τ_e	Torsional fatigue limit

contact area in the wheel. Ahlstörm and Karlsson et al. [2] evaluated the low cycle fatigue behaviors of the wheel material under development. They proposed a heat treatment for the forging and austenite processes to enhance the fatigue strength and mechanical properties. Okagata et al. [3] performed fatigue tests on the actual size wheel. They reported fatigue strength, safety coefficient and design load of the wheel plate. More recently, Wagner et al. [4] investigated the fatigue strain behaviors of the wheel steels at a very high cycle over 10^7 and in terms of microstructural properties. They reported that fatigue behavior changes from cyclic softening to cyclic hardening at 5% of life and dislocation density increased continuously up to 85% of life.

For the railway wheel, multiaxial stress occurs due to the contact load between the wheel steel and rail. However, most studies on the fatigue strength of the railway wheel deal with the uniaxial load. And, there a little number of studies on fatigue strength of wheel treads which is critical to crack initiation.

The purpose of this study is to provide information about the fatigue strength of railway wheel steel for further development towards its safe operation. In this study, specimens of uniaxial and biaxial torsion were extracted from railway wheel steel for fatigue and tensile tests. From these tests, the fatigue limits under uniaxial and torsional loading were evaluated. Then appropriate parameters to predict the fatigue life under multiaxial stress states were reviewed. The results obtained will provide a useful guideline for manufacture and design engineers to evaluate fatigue strength of the wheel steel.

2. Experimental Method

The wheel steel's chemical composition is shown in Table 1. The fatigue specimens for the uniaxial tension and biaxial torsion were extracted from the wheel tread, as shown in Fig. 1. The hardness test was performed from the tread towards the depth's direction to find that the hardness was 106.5 H_{RB} up to 50 mm, indicating that it had more or less the same hardness up to that depth. Therefore, specimens at the tread were extracted until it was 50 mm deep. The configuration and dimension of the uniaxial and biaxial torsional specimens are as shown in Fig. 2.

The fatigue tests were performed with the stress ratio of R= -1 by using uniaxial and biaxial torsional fatigue test specimens at room temperature in air. The tensile tests and uniaxial fatigue tests were performed by using a test device by Instron Inc. with a capacity of 10 tons at 15Hz, whereas the biaxial torsional tests were performed by using a torsional testing device by JT TOHSI Inc.

Table 1. Chemical Composition of Railway Wheel Steel (wt.%).

C	Mn	Si	P	S	Cu	Fe
0.6	0.72	0.28	0.009	0.006	0.02	Rem.

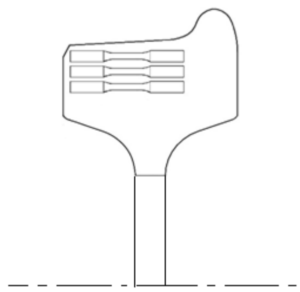
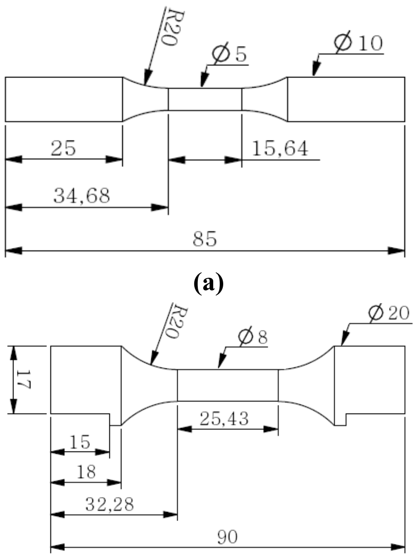


Fig. 1. Position and Orientation of Specimens Extracted from Wheel.



(a)

(b)

Fig. 2. Specimen Configuration for (a) Uniaxial and (b) Torsional Fatigue Specimens.

3. Experimental Results and Discussion

3.1. Tensile tests

Tensile tests were performed by using the specimens extracted from the wheel tread. Curves in Fig. 3 illustrate the engineering strain and true strain against engineering stress and true stress. The engineering stress-strain curve indicates that the maximum tensile strength and yield strength are 1027.7MPa and 626.7MPa, respectively, and the elongation is 40.4%. Meanwhile, the true stress-strain curve shows that the maximum strength is 1319.5MPa and the elongation is 33.9%. Mechanical properties of the railway wheel steel are summarized in Table 2. Hur et al. [5] reported that the tensile strength and elongation of a railway wheel steel are between 836 MPa and 919 MPa and between 18% and 23%, respectively. Kwon et al. [6] also reported that the tensile strength and yield strength of wheel steel for high-speed railway are 1067 MPa and 616 MPa, respectively, and the elongation is 16.2%. The railway steel wheel studied in this study had a similar tensile strength and yield strength to those of the high-speed railway, while its elongation was about 2.5 times superior to that of the high-speed railway.

Table 2. Mechanical Properties of the Railway Wheel Steel.

UTS (MPa)	YS (MPa)	Elong. (%)	σ_f (MPa)	ε_f (%)	σ_e (MPa)	τ_e (MPa)
1027.7	626.7	40.4	1319.5	33.9	422.5	265.0

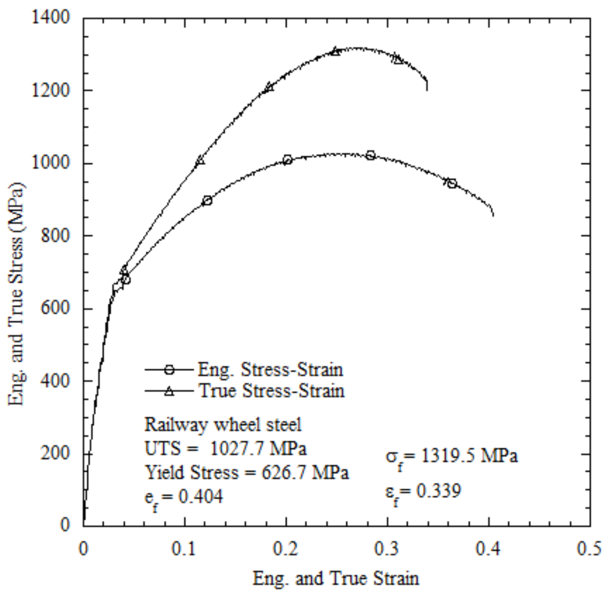


Fig. 3. Engineering and True Stress-Strain Curves of Railway Wheel Steel.

3.2. Fatigue strength

Figure 4 shows the relationship between the maximum principal stress amplitude and the fatigue life from uniaxial and biaxial torsional fatigue tests. According to Fig. 4, the uniaxial and biaxial torsional fatigue limits were 422.5 MPa and 265.0

MPa, respectively. This figure shows that the uniaxial specimen had a longer fatigue life than the biaxial torsional specimen under the same maximum principal stress. The fatigue limit found in the uniaxial fatigue test was 67% of the tensile strength, which is relatively high, compared to about 50% of typical steels. The ratio of the uniaxial fatigue limit against the biaxial torsional fatigue strength τ_e/σ_e was 0.63, and this value is almost the same as 0.6, which is the value for typical ductile materials. For brittle materials, the τ_e/σ_e ratio is known to be about 0.8 or higher, typically [1]. Bernasconi et al. [1] reported that some ductile wheel material has a higher τ_e/σ_e ratio than 0.9, and analyzed that this was attributable to inclusions, such as CaS and MnS in the steel wheel. The fact that the present wheel steel has a high tensile strength and a τ_e/σ_e ratio of 0.63 with a fracture elongation of 40.4% indicates that inclusions, like CaS and MnS, do not exist in large quantities at the wheel steel.

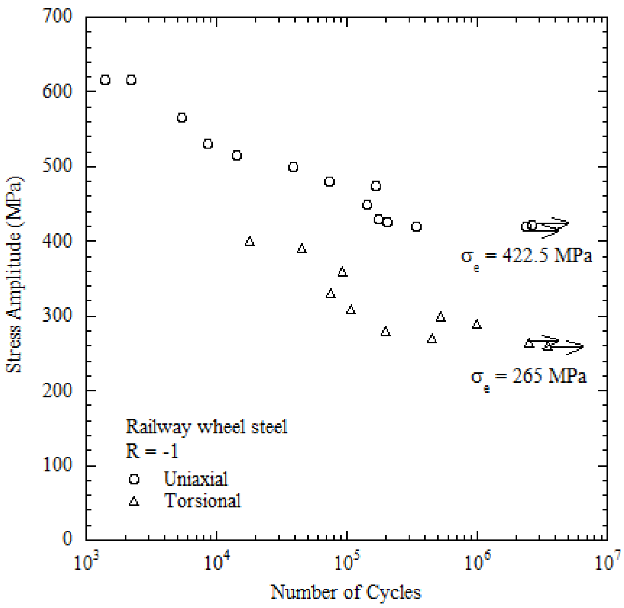


Fig. 4. Stress Amplitude against Number of Cycles for Uniaxial and Biaxial Torsional Fatigue Tests.

3.3. Analysis of multiaxial fatigue strength parameters

This study evaluated the maximum principal stress, equivalent stress, maximum principal strain and equivalent strain as parameters to predict the fatigue life under multiaxial stress states. Figure 4 shows the maximum principal stress amplitude to relate the life of the uniaxial and biaxial torsional fatigue experiment. As a result, this figure found that the fatigue life under different stress states did not agree with each other. In other words, the maximum principal stress was not an adequate parameter to predict the fatigue life under uniaxial and biaxial states.

In general, von Mises equivalent stress σ_{eq} is applied as one of the stress parameters to predict the fatigue life. For torsional biaxial stress, σ_{eq} is equal to

$\sqrt{3}\tau$, whereas for uniaxial stress, $\sigma_{eq} = \sigma_1$. Figur 5 shows the fatigue lifetime for uniaxial and torsional fatigue tests using the von Mises equivalent stress amplitude. The results in Fig. 5 suggest that equivalent stress, just like the maximum principal stress, is not an adequate parameter either to predict the fatigue life in uniaxial and biaxial states with different stress conditions from each other for the wheel steel.

The equivalent strain, another parameter for the strain, was applied to predict the fatigue life under the multiaxial stress states. To determine the equivalent strain for uniaxial and biaxial torsional fatigue tests, $\varepsilon_{eq} = \sigma_1 / E$ was used for the uniaxial test, and $\varepsilon_1 = -\varepsilon_3 = \gamma / 2$, $\varepsilon_2 = 0$, $\varepsilon_{eq} = \sqrt{3}\gamma / 2G(1+\nu)$ were used for the biaxial torsional test. Figure 7 reveals that the equivalent strain is not an adequate parameter to predict the life.

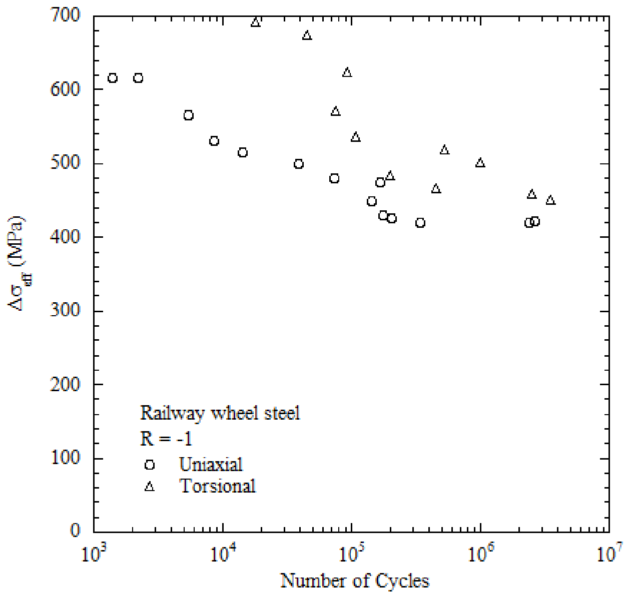


Fig. 5. Von Mises Equivalent Stress Amplitude against the Number of Cycles for Uniaxial and Torsional Fatigue Tests.

The Smith-Watson-Topper multiaxial fatigue parameter (FP) [7] is one of the parameters that can be applied to predict the fatigue life under multiaxial stress states. This model considers that depending upon strain amplitude, material type, and state of stress, materials generally form either shear or tensile cracks. For cracks that grow in planes of high tensile strain. This can be expressed as

$$FP = \sigma_{\max} \frac{\Delta\varepsilon}{2} \tag{1}$$

where $\Delta\varepsilon$ is the difference between the maximum and minimum normal strain to the plane experienced during the cycle and $\sigma_{\max}$ is the maximum stress on the maximum principal strain plane. Figure 7 illustrates the uniaxial and biaxial torsional fatigue lifetimes with the SWT fatigue parameter. Figure 7 also suggests that the SWT fatigue parameter has a correlation coefficient of R = 0.89 and is an adequate parameter to predict the uniaxial and biaxial fatigue lifetimes. It can be concluded from Figs. 5, 6 and 7 that the SWT fatigue parameter is more appropriate parameters than the equivalent strain and equivalent stress to predict life for uniaxial and biaxial fatigue tests.

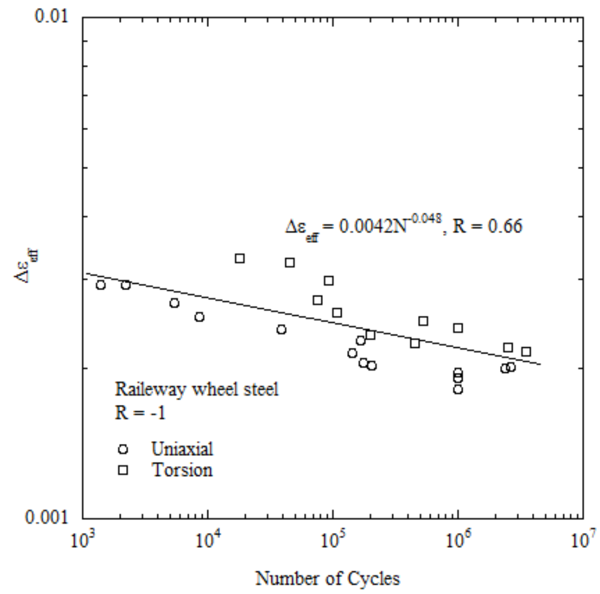


Fig. 6. Equivalent Strain Amplitude against Number of Cycles for Uniaxial and Biaxial Torsional Fatigue Tests.

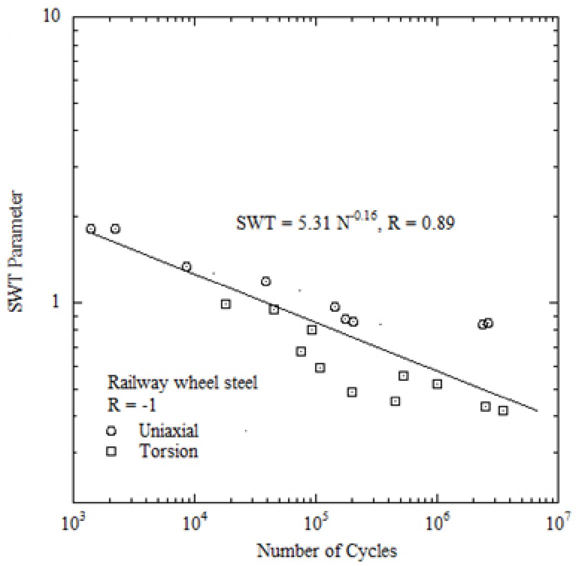


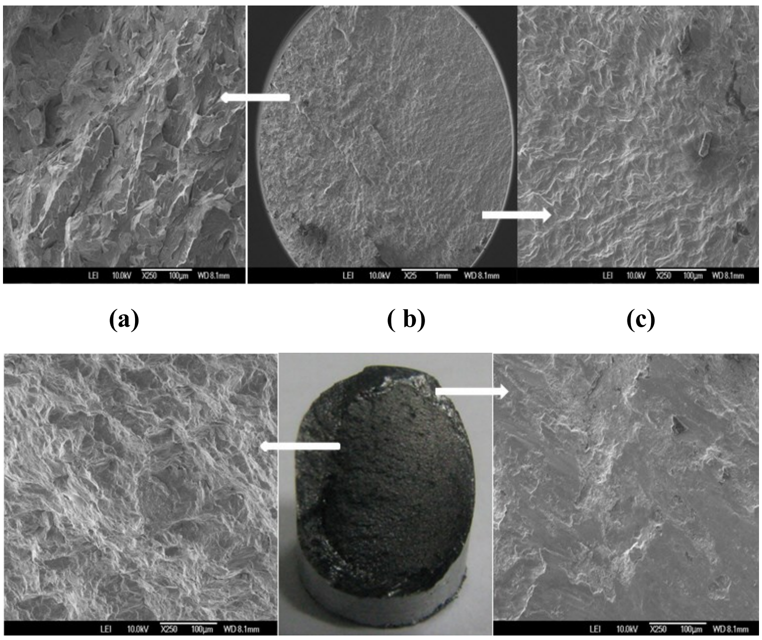
Fig. 7. SWT Parameter against Number of Cycles for Uniaxial and Biaxial Torsional Fatigue Tests.

3.4. Analysis of fatigue fracture surface

Figure 8(a) to (f) show fatigue fracture surfaces for high cycle fatigue lifetime after uniaxial and biaxial torsional fatigue tests. The observation of fatigue fracture surfaces found no inclusions, like CaS and MnS, where the fatigue failure initiated. This finding reconfirms the fact that the typical τ_e / σ_e ratio of the railway wheel steel of this study is 0.63, indicating that there are few inclusions like CaS and MnS.

Figures 8 (a), (b) and (c) show the fracture surface at the uniaxial specimen ($\Delta\sigma/2$ = 421 MPa, N_f = 342412 cycles), and Fig. 8(b) suggests that the surface was fractured almost vertically to the axial load angle, and is visibly very smooth. Fatigue crack initiated at 4:30 angle of the image at the center, and consequently, crack propagated in to the remaining area. Figure 8(a) shows a typical final fractured surface with a cleavage fracture mode.

Figures 8(d), (e) and (f) show the fracture surfaces at the biaxial torsional specimen ($\Delta\tau/2$ = 300 MPa, N_f =523615 cycles), and Fig. 8(e) indicates that the surface was fractured on a 40 degree slope against the axial load angle. Fatigue crack initiation occurred on the outside of the cylindrical specimen. It also shows that the final fracture took place at the center of the specimen. For the fractured surface where fatigue cracks propagated, the surfaces are smeared due to friction between the fractured surfaces in contact with each other at torsional fatigue, as shown in Fig. 8(f). Figure 8(d) shows a typical final fractured surface with a combination of a visible cleavage fracture mode and a ductile fracture mode.



(a) (b) (c)

(d) (e) (f)

Fig. 8. Fatigue Fracture Surfaces of (a), (b) and (c) Uniaxial Specimen at $\Delta\sigma/2$ = 421 MPa and (d), (e) and (f) Torsion Specimen at $\Delta\tau/2$ = 300 MPa.

4. Conclusions

This study performed fatigue tests on uniaxial and biaxial torsional specimens of a railway wheel steel. The testing results are as follows:

- The tensile tests found that the ultimate tensile strength and yield strength were 1027.7 MPa and 626.7 MPa, respectively, and the elongation was 40.4%.
- The uniaxial fatigue limit was 422.5 MPa, or 67% of the tensile strength, and τ_e / σ_e, which is the ratio of the uniaxial fatigue limit against the biaxial torsional fatigue limit, was 0.63, which is the value for typical ductile materials.
- The study found that the SWT fatigue parameter is more adequate parameters to predict the fatigue life for uniaxial and biaxial fatigue tests than the equivalent strain or equivalent stress under multiaxial stress states.

Acknowledgment

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References

1. Bernasconi, A.; Filippini, M.; Foletti, S.; and Vaudo, D. (2006). Multiaxial fatigue of a railway wheel steel under non-proportional loading. *International Journal of Fatigue*, 28(5-6), 663-672.
2. Ahlstrӧm, J.; and Karlsson, B. (2009). Modified railway wheel steels: Production and evaluation of mechanical properties with emphasis on low-cycle fatigue behavior. *Metallurgical and Materials Transactions A*, 40(7) 1557-1567.
3. Okagata, Y.; Kiriyama, K.; and Kato, T. (2007). Fatigue strength evaluation of the Japanese railway wheel. *Fatigue & Fracture of Engineering Materials & Structures*, 30(4), 356-371.
4. Wagner, V.; Starke, P.; Kerscher, E.; and Eifler, D. (2011). Cyclic deformation behavior of railway wheel steels in the very high cycle fatigue (VHCF) regime. *International Journal of Fatigue*, 33(1), 69-74.
5. Hur, H.M.; and Kwon, S.J. (2004). An analysis of material test results for rolling-stock wheel. *Proceedings of Korean Society of Railway*, 153-157.
6. Kwon, S.-J.; Seo, J.-W.; Lee, D.-H.; and Ham, Y.-S. (2010). Fracture mechanics characteristics of wheel and axle for high speed train. *Journal of the Korean Society for Precision Engineering*, 27(8), 28-34.
7. Bannantine, J.A.; and Comer, J.J.; Handrock, J.K. (1990). *Fundamentals of metal fatigue analysis.* Prentice Hall Inc.