Effect of Microstructure on Torsional Fatigue Endurance of Martensitic Carbon Steel*

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Abstract

The microstructural influence of martensitic carbon steel on torsional fatigue endurance was investigated, taking into consideration the application of high strength steel electric resistance welded (ERW) tubes to automotive structural parts. The chemical composition of the base steel alloy was 0.1-0.2%C-0.2-1.5%Si-1.3-1.9%Mn-0.01%P-0.001%S-(Cr,Mo,Ti,Nb,B). Laboratory vacuum-fused ingots were hot-rolled, heated to 1023 or 1223 K in a salt bath, and then water-quenched and tempered at 473 K. Consequently, three types of microstructure, martensite (M), martensite and ferrite (M+F), and ferrite and pearlite (F+P), were prepared. Fully reversed torsional fatigue testing was conducted with 6 mm diameter round bar specimens. Torsional fatigue endurance was found to monotonously increase with increases in the tensile strength of the specimen from 540 to 1380 MPa. The martensitic single structure and the M+F dual-phase structure showed a similar level of fatigue endurance at a tensile strength of approximately 950 MPa. However, fatigue micro-crack morphology varied slightly between them. At the surface of the M+F specimen, many small cracks were observed in addition to the main crack. Conversely, in the martensitic specimen, these small cracks were rarely observed. ΔK decreasing/increasing crack growth testing with compact tension (CT)-type specimens was also conducted. Based on these experimental results, the effect of microstructure and stress level on the initiation/propagation cycle ratio is discussed. In addition to fatigue properties, some practical properties, such as low-temperature toughness and hydrogen embrittlement resistance, were also evaluated in view of actual applications for automotive structural parts.

Key words: Torsional Fatigue Test, Crack Growth Rate, Martensite, Microstructure, High Strength Carbon Steel, Low-Temperature Toughness, Hydrogen Embrittlement

1. Introduction

In order to reduce the weight and size of suspension parts, steel tubes have increasingly been used in recent years⁽¹⁾⁻⁽³⁾. When particularly high static strength and fatigue endurance are required, quenching, i.e., using a martensitic microstructure, is an effective method of strengthening. The effect of microstructure on the fatigue endurance of steel has been intensively investigated. Kurita *et al.* examined the effect of strengthening mechanisms on the fatigue endurance of F+P and F+M-based microstructures under tension-compression

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axial loading ⁽⁴⁾⁽⁵⁾. Wang *et al.* studied the effect of martensite volume fraction and morphology on the fatigue crack growth rate of a F+M microstructure under tension-zero cycling ⁽⁶⁾⁽⁷⁾. However, the microstructural influence of 800 MPa and higher tensile strength grade steel on fatigue endurance has not been fully clarified yet.

In this study, we conducted torsional fatigue and CT-type crack growth tests on 0.1-0.2%C-0.2-1.5%Si-1.3-1.9%Mn-0.01%P-0.001%S-(Cr,Mo,Ti,Nb,B)-based martensitic high-tensile strength steels. Based on these experimental results, the effects of microstructure and stress level on the initiation/propagation cycle ratio are discussed.

2. Nomenclature

a_i	initial fatigue crack length	N_c	crack propagation cycle number
a_c	final fatigue crack length	R	stress ratio
C	crack growth law coefficient	s	crack length
da/dN	crack growth rate	V_f	volume fraction of ferrite
d_f	ferrite grain size	ΔK	$K_{max} - K_{min}$ in a fatigue cycle
d_{mp}	martensite packet size	ΔK_{th}	threshold stress intensity factor range
F	correction factor	$\Delta\sigma$	nominal stress
m	crack growth exponent	ρ	notch root radius

3. Experimental

The chemical compositions of the steels used in this study are listed in Table 1, along with the desired microstructure ⁽⁸⁾. Cr, Mo, Ti, Nb, and B were arbitrarily added in order to adjust the hardenability and grain size of the specimens. Figure 1 shows the hot-rolling and heat-treatment conditions of the specimens. Laboratory vacuum-fused ingots were hot-rolled, and then one was heated to the austenite-ferrite dual-phase region at 1023 K while the other was heated to the austenite region at 1223 K in a salt bath. Both were immediately water-quenched and subsequently tempered at 473 K. As shown in Fig. 2, three types of microstructure, martensite (M), martensite and ferrite (M+F), and ferrite and pearlite (F+P), were prepared after the heat treatment. The material heated to the austenite-ferrite dual-phase region, MF, shows the martensite and ferrite structure (volume fraction of ferrite, $V_f = 45\%$; ferrite grain diameter, $d_f = 20 \mu\text{m}$), while the material heated to the austenite region, M1-M3, exhibits the martensite structure (martensite packet diameter, $d_{mp} = 10 \mu\text{m}$). The ferrite and pearlite structure ($V_f = 76\%$; ferrite grain diameter, $d_f = 30 \mu\text{m}$) is an as-hot-rolled material used for comparison (FP1). Microstructural anisotropy and band structure were not observed in these specimens. Table 2 shows the tensile properties and volume fraction of microstructure of the specimens. The tensile strength varied from 540 to 1380 MPa.

Figure 3 shows the round bar-type torsional fatigue test specimen with a 6 mm diameter and a 15 mm long parallel portion. Torsional fatigue characteristics were evaluated under a stress ratio of $R = -1$ and a repetition rate of 33 Hz. The surface was machine-finished. Scanning electron microscope (SEM) observation was conducted on a cross-section of the surface of the round bar specimen after the fatigue test. The surface was etched with 2% Nital. Transmission electron microscope (TEM) observation was carried out for some samples after the fatigue test.

ΔK decreasing/increasing crack growth tests were carried out with separately prepared CT-type specimens, as shown in Fig. 4. The crack growth test was performed under sinusoidal loading at a frequency of 15 Hz with a stress ratio of $R = 0.1$. Table 3 shows the Vickers hardness and microstructure of the crack growth test specimens. The chemical composition is the same as for FP1 and M3 in Table 1. Hot-rolling and heat-treatment

Table 1 Chemical composition of steel used.

Material	Chemical composition (mass %)						Microstructure [aim]
	C	Si	Mn	P	S	Others	
FP1	0.18	0.2	1.3	0.01	0.001	Cr, Ti, Nb, B	F+P
MF	0.13	1.5	1.9	0.01	0.001	Cr, Mo, Ti, Nb	M+F
M1	0.10	0.4	1.9	0.01	0.001	Cr, Mo, Ti, Nb	M
M2	0.14	0.4	1.9	0.01	0.001	Cr, Mo, Ti, Nb	
M3	0.18	0.2	1.3	0.01	0.001	Cr, Ti, Nb, B

Fig. 1 Hot-rolling and heat-treatment condition.

Fig. 2 Optical micrographs of heat-treated specimens for torsional fatigue test; (a) TS 540 MPa ferrite and pearlite (FP1), (b) TS 920 MPa martensite and ferrite (MF), (c) TS 1380 MPa martensite microstructure (M3).

Table 2 Tensile properties and volume fraction of microstructure of specimens.

Material	Tensile properties*				HV (10)	Microstructure
	YS (MPa)	TS (MPa)	YR (%)	El (%)		
FP1	340	540	63	34	157	F+P ($V_f=76\%$, $d_f=30\mu\text{m}$)
MF	690	920	75	18	274	M+F ($V_f=45\%$, $d_f=20\mu\text{m}$)
M1	720	970	75	17	313	M ($d_{mp}=10\mu\text{m}$)
M2	890	1170	76	12	359	
M3	1110	1380	80	13	442	

*: JIS13B half; 5 mm^L; gauge length=25mm

conditions are indicated in Fig. 1. The crack growth direction was transverse to the hot-rolling direction. In the crack growth test, a stepwise ΔK decreasing procedure was used to obtain the threshold value. The threshold stress intensity factor range, ΔK_{th} , was determined as the ΔK at which no crack growth was observed for 2×10^6 cycles. Subsequently, a ΔK - increasing test was conducted to obtain the entire crack growth curve.

The initial fatigue crack length was 12 mm and the initial ΔK value was $22 \text{ MPa}\sqrt{\text{m}}$. Prior to the fatigue crack test, the specimen surface was etched with 2% Nital to allow for in-situ crack growth observation with an optical microscope.

4. Results and Discussion

Figure 5 shows the relationship between stress amplitude and fatigue endurance in the torsional fatigue test. Monotonous improvement of fatigue endurance is obtained by an increase in tensile strength in the range from 540 to 1380 MPa. M1 and MF, both having a tensile strength of about 950 MPa, show almost the same fatigue endurance independent of the loading stress level.

Figure 6 shows SEM micrographs of a cross-section at the surface of the round bar specimen after the torsional fatigue test. At the surface of the FP1 and MF specimens, many small cracks were observed in addition to the main crack. Conversely, these small cracks were rarely observed at the surface of the martensite single structure specimen.

Figure 7 shows SEM micrographs of a cross-section at the surface along main cracks. The main cracks of the F+P and M+F dual-phase specimens have propagated irrespective of microstructure except at the surface.

Fig. 3 Round bar-type torsional fatigue test specimen. Fig. 4 CT-type crack growth test specimen (9.5 mm^3).

Table 3 Vickers hardness and microstructure of the crack growth test specimens.

Material	HV (10)	Microstructure
FP2	155	F+P ($V_f=75\%$, $d_f=22 \mu\text{m}$)
FM	235	F+M ($V_f=65\%$, $d_f=19 \mu\text{m}$)
M4	433	M ($d_{mp}=15 \mu\text{m}$)

Fig. 5 Relationship between stress amplitude and fatigue endurance in the torsional fatigue test.

Fig. 6 SEM micrographs of a cross-section at the surface of the round bar specimen after the torsional fatigue test; (a) TS 540 MPa ferrite and pearlite (FP1) at $\tau = \pm 400$ MPa to $N = 8000$ cycles, (b) TS 920 MPa martensite and ferrite (MF) at $\tau = \pm 500$ MPa to $N = 7000$ cycles, (c) TS 970 MPa martensite (M1) at $\tau = \pm 500$ MPa to $N = 9000$ cycles.

Fig. 7 SEM micrographs of a cross-section at the surface along main cracks; (a) TS 540 MPa ferrite and pearlite (FP1) at $\tau = \pm 250$ MPa to $N = 2.03 \times 10^5$ cycles, (b) TS 920 MPa martensite and ferrite (MF) at $\tau = \pm 500$ MPa to $N = 7000$ cycles, (c) TS 970 MPa martensite (M1) at $\tau = \pm 500$ MPa to $N = 9000$ cycles, (d) TS 1380 MPa martensite (M3) at $\tau = \pm 600$ MPa to $N = 41000$ cycles.

Figure 8 shows SEM macro- and micrograph on the surface of the TS 540MPa ferrite and pearlite (FP1) specimen. The cracks initiated in the ferrite grain and propagated parallel and perpendicular to the axial directions that were the same as maximum shear stress direction. Then, the cracks branched to the maximum tensile stress direction. The cracks of the TS 920MPa martensite and ferrite (MF) specimen also initiate in ferrite grain (arrows in Fig. 9 (b)) and then branched. The cracks of the TS 970 MPa martensite (M1) also indicate initiation in the shear stress direction and branching (shown in Fig. 10). However, the number of initiated cracks and the ratio of branched element seems to be smaller than in the FP1 and MF specimens. On the surface of the TS 1380MPa martensite (M3) specimen, the surface micro cracks were rarely observed, as shown in Fig. 11. The influence of stress level on crack path has not been observed in these specimens.

Figure 12 shows SEM macrographs of fracture surface. The cracks propagated mainly perpendicular to the axis direction; however, microscopically, the cracks also have an

Fig. 8 SEM micrograph on the surface of the TS 540 MPa ferrite and pearlite (FP1) specimen at $\tau = \pm 300$ MPa to $N=55000$ cycles.

Fig. 9 SEM micrograph on the surface of the TS 920 MPa martensite and ferrite (MF) specimen at $\tau = \pm 400$ MPa to $N=47000$ cycles.

Fig. 10 SEM micrograph on the surface of the TS 970 MPa martensite (M1) specimen at $\tau = \pm 400$ MPa to $N=34000$ cycles.

Fig. 11 SEM micrograph on the surface of the TS 1380MPa martensite (M3) specimen at $\tau = \pm 500$ MPa to $N=1.11 \times 10^5$ cycles.

inclined direction element, which is also observed in the macrographs of Fig. 8 – Fig. 11. Crack coalescence also occurred on the way to final fracture.

Figure 13 shows the TEM micrograph near the surface of the M1 specimen after a torsional fatigue test. It shows the typical dislocation cell structure similar to that observed in a soft ferrite matrix after fatigue testing in previous studies⁽⁵⁾⁽⁷⁾.

Figure 14 shows $da/dN-\Delta K$ curves of the FP2, FM, and M4 specimens. The threshold

Fig. 12 SEM macrographs of fracture surface.

stress intensity factor range, ΔK_{th} , value decreased slightly from 10 to 8 $\text{MPa}\sqrt{\text{m}}$ with an increase in hardness of the specimen. This may be due to the decrease of plastic formability at the crack tip. Regression lines of the da/dN - ΔK curves are re-plotted in Fig. 15.

To consider the reason why specimens FM and M1 show almost the same fatigue endurance independent of the loading stress level, the propagation cycle number was estimated by the Paris law as follows:

$$\frac{da}{dN} = C(\Delta K)^m \quad (1)$$

where C and m are material constants.

The crack propagation cycle number, N_c , can then be derived from following equation:

$$N_c = \int_0^{N_c} dN = \int_{a_i}^{a_c} \frac{1}{C(\Delta K)^m} da = \int_{a_i}^{a_c} \frac{da}{C(\Delta \sigma \sqrt{\pi a} \cdot F)^m} =$$

$$\frac{1}{C(\Delta \sigma \sqrt{\pi} \cdot F)^m} \int_{a_i}^{a_c} \frac{1}{(\sqrt{a})^m} da = \frac{2\{a_i^{-(m-2)/2} - a_c^{-(m-2)/2}\}}{(m-2)C(\Delta \sigma \sqrt{\pi} \cdot F)^m} \quad (2)$$

where a_i and a_c are the initial and final fatigue crack lengths. $\Delta \sigma$ and F are the nominal

Fig. 13 TEM micrographs near the surface of the TS 970 MPa martensite specimen (M1); (a) initial, (b) at $\tau = \pm 500$ MPa to $N = 9000$ cycles.

Fig. 14 da/dN - ΔK curves of the (a) FP2, (b) FM, and (c) M4 specimens.

Fig. 15 Regression lines of the da/dN - ΔK curves re-plotted from Fig. 8.

stress and the correction factor, respectively.

Based on Eq. (2), the crack propagation cycle number, N_c , from a_i to a_c was calculated as a function of $\Delta\sigma$ for (1) FP1, (2) MF and M1 (MF-M1), and (3) M3. The total fatigue cycle number of MF and M1 were approximately the same; thus, they were considered together. The calculation parameters are listed in Table 4.

In a previous study⁽⁸⁾, the propagation cycle number was calculated using reference C and m data⁽⁹⁾⁻⁽¹⁴⁾. In this study, we estimated N_c based on the C and m value extracted from a linear approximation of the data in Fig. 8 in the Paris regime, which ranges from $\Delta K = 12$ to $20 \text{ MPa}\sqrt{\text{m}}$. For the C and m values for FP1, MF-M1, and M3 specimens, the values of FP2, FM, and M4 were respectively substituted. The a_i value for FP1, MF-M1, and M3 was altered depending on their grain or packet size. 30, 20, and $10 \text{ }\mu\text{m}$ were substituted, respectively. The radius of the test specimen (3 mm) was adopted as the a_c value. According to Eq. (3)⁽¹⁵⁾, the value of F is 4.5916 when $\rho = 0$.

$$F = 4.5916 \exp \{-0.6759 \times (s/\rho)\} \quad (3)$$

where s and ρ are the crack length and the notch root radius, respectively. Furthermore, in this study, F was multiplied by the crack correction factor for a surface semicircle $(0.728)^{(16)}$.

As seen in Fig. 6 – Fig. 13, the crack propagation stage includes both tensile and shear modes in the torsional fatigue test. However, crack growth rate in shear mode of the specimens used has not been separately evaluated. Nishizawa *et al.* reported that the crack growth rate of SUJ2 in Mode I and II overlaps around $da/dN = 10^{-8} \text{ m/cycle}$ region⁽¹⁷⁾. Thus, for the primary approximation, the crack growth rate in tensile mode was applied for the N_c calculation in this study.

Figure 16 shows the relationship between $\Delta\sigma$ and the calculated propagation and initiation cycle number on a linear scale. The balance of the total fatigue cycle, i.e., the total cycle number minus the calculated propagation cycle number, is regarded as the initiation cycle number. Figure 17 shows the re-plotted data of Fig. 16. With an increase in $\Delta\sigma$, the ratio of the propagation cycle number increases as experimentally reported in a previous study⁽¹⁸⁾. It also appears that with an increase of material strength, the ratio of the propagation cycle number decreases as previously reported⁽¹⁹⁾.

Regardless of the initiation/propagation cycle ratio, which varies with $\Delta\sigma$, the total fatigue cycle number of MF and M1 are almost the same as shown Fig. 5. Therefore, it can be assumed that their initiation and propagation cycle numbers are individually almost the same. Thus, the growth of a discrete surface crack in the ferrite phase of the FM specimen shown in Fig. 6 (b) might be retarded by the surrounding martensite before the crack becomes an indiscrete initial crack. Consequently, the initial crack in FM seems to behave as if it is in a homogeneous microstructure, which is schematically described in ref.⁽²⁰⁾.

As stated above, the simple calculation readily describes the tendency of initiation/propagation fatigue phenomena. However, it is based on many presumptions and approximations. Therefore, for further quantitative estimation and discussion, many other influencing factors such as the effect of stress mode, stress ratio, crack closure, crack coalescence, and surface residual stress must be clarified and taken into account.

5. Low Temperature Toughness and Hydrogen Embrittlement Resistance of Martensitic Low Carbon Steel for Automotive Structural Parts

Based on the above examination for fatigue endurance, martensite single phase is adopted as the basic microstructure for quench-type automotive structural parts. This is because it has advantages for some practical properties, such as low temperature toughness and hydrogen embrittlement resistance after quenching by providing a higher strength with a smaller amount of alloying elements than the dual-phase microstructure⁽²⁰⁾.

Table 4 N_c calculation parameters.

Material	Crack growth parameter			Initial and final crack length		Correction factor, F
	C (m/cycle)	m	Ref.	a_i (μ m)	a_c (mm)	
FP1	9.27×10^{-15}	5.05	FP2	30	3	3.34
MF-M1	9.30×10^{-14}	4.27	FM	20		
M3	1.10×10^{-12}	3.50	M4	10

Fig. 16 The relationship between $\Delta\sigma$ and the calculated propagation and initiation cycle number of (a) FP1, (b) MF-M1, and (c) M3 specimens.

Fig. 17 Calculated propagation/total cycle ratio re-plotted from Fig. 16.

A laboratory vacuum-fused steel having a base composition of 0.14-0.2%C-0.3%Si-1.5%Mn-0.01%P-0.001%S-(Cr,Mo) was hot-rolled, heated to an austenite single-phase region at 1223 K, then quenched by water, and finally tempered at 473 K. A 2 mm V-notched Charpy specimen was fabricated from this treated sheet material for evaluation of impact characteristics, and a four-point bending specimen was also made to carry out a four-point bending test ⁽²¹⁾ under a loading stress of 1180 MPa in 1N-hydrochloric acid.

Table 5 shows the Charpy impact characteristics and the four-point bending test results. All the tested specimens showed good impact characteristics, with 80 J/cm² or higher absorbed energy at 273 K and 213 K or lower fractured face transition temperature. The four-point bending test in 1N-hydrochloric acid produced no cracks over 240 h, showing excellent hydrogen embrittlement resistance. Observation of the microstructure by SEM showed that all the specimens had fine carbide precipitation in a martensitic lath structure, as in ref. ⁽²¹⁾. It is clarified that, similarly to the case of high strength cold-rolled steel sheets ⁽²²⁾, the low carbon equivalent effectively gives excellent impact characteristics and hydrogen embrittlement resistance to hot-rolled-based martensite microstructures.

Table 5 Charpy impact properties and delayed fracture resistance of low-carbon martensite single-phase steel.

HV10	Charpy impact properties (1/4 size)		Delayed fracture resistance*
	vE0 (J/cm ²)	vTrs (K)	Time to fracture (h)
431	113	173	>240
454	103	193	>240

• HV10: Vickers hardness obtained using a 10kgf force
 • vE0: Charpy absorbed energy at 273K
 • vTrs: Charpy fracture appearance transition temperature
 *: Loading stress=1180MPa; in 1N hydrochloric acid solution

6. Conclusions

The effect of the microstructure of martensitic carbon steel on torsional fatigue endurance was investigated, taking into consideration the application of high strength steel electric resistance welded (ERW) tubes to automotive structural parts.

- (1) Torsional fatigue endurance was found to monotonously increase with an increase in tensile strength in the range of 540 to 1380 MPa. The martensite and ferrite dual-phase specimen, MF, and the martensite single-phase specimen, M1, both having a tensile strength of about 950MPa, showed almost the same fatigue endurance independent of the loading stress level.
- (2) Based on the crack growth test results, the propagation cycle number was calculated using the Paris law. With an increase of $\Delta\sigma$ and with a decrease in material strength, the ratio of the propagation cycle number was found to increase using this calculation.
- (3) In addition to fatigue properties, low-temperature toughness and hydrogen embrittlement resistance were also evaluated for the low-carbon martensite single-phase steel.

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