Fatigue Strength Characteristics of High-Strength Steel*

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In order to clarify the fatigue strength characteristics of low-alloy steels tempered at low temperature (150~200°C) or carburized in generated gas, rotating bending fatigue tests were conducted in laboratory air and dry air. The influence of moisture in air was only observed for the carburized steel. The low-temperature-tempered steel revealed two knees on the S-N diagram, and no fatigue limit was found up to 10^9 cycles (9 months). The carburized steel revealed three knees and the fatigue limit was found over 10^8 cycles. When the fatigue test of carburized steel was carried out in dry air or the surface structure anomalies were removed, the fatigue strengths were improved, but neither knees nor fatigue limits were found up to 10^9 cycles. The reasons for this were discovered from the results of fractography and the equations proposed by Murakami *et al.* for the prediction of the fatigue limit of steel with microdefects.

Key Words: Fatigue, S-N Curve, Fatigue Limit, High-Strength Steel, Low-Temperature Tempering, Carburizing, Fish-Eye Fracture, Inclusion, Moisture, Vickers Hardness

1. Introduction

Low-temperature tempering and carburizing are often used as simple means of obtaining high-strength steels. The fatigue strength characteristics of low-temperature-tempered or carburized steels in the long life range over 10^7 cycles, however, have hardly been clarified⁽¹⁾⁻⁽⁴⁾. On the other hand, since mechanical properties of high-strength steels are sensitive to environment, it is anticipated that even moisture in the air may influence those fatigue strength characteristics. Studies on this problem are also very few in number.

This study, therefore, aims to clarify the fatigue strength characteristics of low-alloy steels tempered at low temperature or carburized in generated gas, with particular attention paid to the long life range over 10^7 cycles and the influence of moisture in air.

2. Materials and procedure

Steels tempered at low temperatures were JIS SCM 435 (two charges, A and B) and SNCM 439, the chemical compositions for which are shown in Table 1. For the purpose of comparison, those tempered at high temperature (conventional tempering temperature) were also made available. The heat treatment conditions and the mechanical properties after the heat treatments are shown in Fig. 1 and Table 2, respectively. The tensile strengths of steels tempered at low temperatures were at least twice those of the steels tempered at high temperature.

Steels carburized in generated gas with 0.8% carbon potential were JIS SCM 420 and SNCM 420,

Table 1 Chemical compositions of Cr-Mo steel (JIS SCM 435) and Ni-Cr-Mo steel (JIS SNCM 439)

Material		C	Si	Mn	P	S	Cr	Mo	Ni
SCM435	A	0.36	0.20	0.82	0.013	0.007	1.10	0.16	—
	B	0.38	0.27	0.80	0.015	0.012	1.07	0.17	—
SNCM439		0.38	0.27	0.68	0.010	0.010	0.75	0.19	1.72

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Table 2 Mechanical properties of low/high-temperature-tempered Cr-Mo steel (JIS SCM 435) and Ni-Cr-Mo steel (JIS SNCM 439)

	SCM435				SNCM439	
	150°C		600°C		200°C	600°C
	A	B	A	B		
Yield Point (MPa)	1411	1515	902	947	1440	924
Tensile Strength(MPa)	1910	2122	972	1031	1970	1040
Elongation (%)	11.5	10.3	19.3	18.8	11.0	17.5
Reduction of Area (%)	49.0	43.8	69.4	57.3	43.5	54.6
Hardness HV	529	555	306	314	562	327

Table 3 Chemical compositions of Cr-Mo steel (JIS SCM 420) and Ni-Cr-Mo steel (JIS SNCM 420)

Material	C	Si	Mn	P	S	Cu	Ni	Cr	Mo
SCM420	0.22	0.27	0.75	0.016	0.020	0.16	0.11	1.05	0.16
SNCM420	0.20	0.30	0.55	0.015	0.013	0.14	1.64	0.53	0.16

Fig. 1 Conditions of low/high temperature tempering heat treatment

the chemical compositions of which are shown in Table 3. The conditions of carburizing, quenching and tempering are shown in Fig. 2. The Vickers hardness distributions after these heat treatments are shown in Fig. 3. The hardness values near the surfaces of both steels decreased, because of the presence of surface structure anomalies which consisted of internal oxides (about $8\mu\text{m}$ in depth) and nonmartensitic microstructures (about $30\mu\text{m}$ in depth). The effective case depth based on the hardness of 550 HV was about 0.8 mm for both steels, while the total case depth was 1.4 mm or so for SCM420 steel, and about 1.6 mm for SNCM 420 steel.

The design of the fatigue specimen used in this study is shown in Fig. 4. Tempered specimens were finished by polishing with emery paper after the heat treatments, while carburized specimens were finished before the heat treatments. The surface layer of some

Fig. 2 Condition of carburizing heat treatment

carburized specimens was ground off to a depth of 0.1 mm, in order to find the influence of surface structure anomalies on the fatigue strength characteristics.

Rotating bending fatigue machines of 98 N·m in load capacity and 2 850 rpm in cyclic speed were used for the fatigue tests, which were carried out in laboratory air. Furthermore, the tempered SNCM 439 specimen, and the carburized SCM 420 and SNCM 420 specimens were also tested in dry air whose dew point was about -70°C , in order to clarify the influence of moisture in air on the fatigue strength characteristics. The apparatus shown in Fig. 5 was constructed so that the air would become dry only at the portion to be tested.

Fractographic features near the fracture origins were observed by a scanning electron microscope.

Fig. 3 Vickers hardness distributions of carburized steels

Fig. 4 Shape and dimensions of fatigue test specimen

Fig. 5 Appearance of fatigue test in dry air

3. Experimental results

3.1 Low-temperature-tempered steels

3.1.1 SCM 435 Results of fatigue tests are shown in Fig. 6. In the case of specimens tempered at 600°C (high tempering temperature), the forms of S-N diagrams were normal for both charge A and B specimens. The fatigue limits were about 480 MPa and 510 MPa, respectively. In the case of the specimens tempered at 150°C (low tempering temperature), on the other hand, the forms of S-N diagrams were markedly different from those of the 600°C -tempered specimens. That is, two knees were recognized on the S-N diagrams, which dropped linearly even in the long life range over 10^7 cycles, without fatigue limits up to 3×10^8 cycles. Moreover, it should be noted that large scatters were found on the fatigue strengths.

3.1.2 SNCM 499 Results of fatigue tests are shown in Fig. 7. In the case of specimens tempered at

Fig. 6 S-N diagrams of low/high-temperature-tempered SCM 435 steels

Fig. 7 S-N diagrams of low/high temperature tempered SNCM 439 steels

600°C, the form of the S-N diagram was normal and the fatigue limit was about 580 MPa. In the case of specimens tempered at 200°C, the presence of two knees and the large scatter of fatigue strength were similar to the results of the SCM 435 150°C-tempered specimen, and no fatigue limit was found up to about 10^9 cycles.

No obvious difference was recognized in the results between laboratory air and dry air. Consequently, it is said that moisture in air does not influence fatigue strengths of steels tempered at low or high temperatures.

3.2 Carburized steels

3.2.1 SCM 420 Results of fatigue tests are shown in Fig. 8. The S-N diagram of the as-carburized specimen revealed three knees on the curve, and the third knee, which was found at about 10^8 cycles, corresponded to the fatigue limit. The value (500 to 560 MPa) of the fatigue limit was nearly the same as those (480~600 MPa) of high-temperature-tempered specimens.

The fatigue strength of the ground-off specimen without surface structure anomalies became higher than that of the as-carburized specimen with surface structure anomalies, but neither knee nor fatigue limit in the S-N diagram was found up to about 10^9 cycles. It should be noted that the ground-off specimen to which cyclic stress of 1 060 MPa was applied did not fail up to 3.5×10^8 cycles. The reason will be discussed later on.

In the short life range up to 10^5 cycles (the first knee), no obvious difference was recognized in the results between laboratory air and dry air on the fatigue strength of the as-carburized specimen. When the number of stress cycles exceeded 10^6 cycles (the second knee), the fatigue strength in dry air became higher than that in laboratory air, and then coincided with that of ground-off specimens tested in laboratory

air. The reason will also be discussed later.

3.2.2 SNCM 420 Results of fatigue tests are shown in Fig. 9. The fatigue strength characteristics are similar to those of SCM 420 steel given above.

4. Discussion

4.1 Low-temperature-tempered steels

As described in section 3.1, the fatigue strength characteristics of low-temperature-tempered specimens were markedly different from those of high-temperature-tempered specimens. Namely, (1) two knees were recognized in the S-N diagrams, (2) which dropped linearly even in the long life range over 10^7 cycles, (3) without obvious fatigue limits in the test range up to 10^9 cycles, and (4) with large scatters of fatigue strength.

Observation results of fracture surfaces revealed that the fractures in the low-temperature-tempered specimens in the short life range up to the first knee had surface origins, while those in the long life range over the second knee mainly had subsurface origins. In the case of subsurface origin (fish-eye-type fracture), the mark "f" was added to each test point in Figs. 6 and 7. Consequently, it is concluded that the phenomenon mentioned in (1) was induced by the difference of location of fracture origin.

An example of fish-eye-type fracture surfaces is shown in Fig. 10. A nonmetallic inclusion was observed at the fracture origin, and it is clear that the inclusion became the initiation of fatigue fracture. Therefore, it seems that the inclusion was related to the phenomena mentioned in (2) to (4).

Furthermore, the crucial problem is that the fatigue limits of low-temperature-tempered specimens may become lower than those of high-temperature tempered specimens. This problem will be investigated according to the following equation⁽⁵⁾ proposed by Murakami and Endo for the prediction of

Fig. 8 S-N diagrams of carburized SCM 420 steels

Fig. 9 S-N diagrams of carburized SNCM 420 steels

fatigue limit of steel with surface microdefects, since the inclusions observed at the fracture origins are deemed as a microdefect and were very close to the specimen surface as shown in Fig. 10 ;

$$\sigma_w = 1.43(H_v + 120)/(\sqrt{\text{area}})^{1/6} \quad (1)$$

where σ_w is the predicted fatigue limit (MPa), H_v is the Vickers hardness of the specimen (kgf/mm²), and $\sqrt{\text{area}}$ is the square root at the area (μm) of the defect projected onto the plane normal to the direction of maximum tensile stress.

It is assumed that a spherical defect, whose diameter is equal to the maximum value (see Table 4) of sizes of inclusions observed at the fracture origins, is adjacent to the specimen surface. As the severest condition, the area in Eq. (1) can be taken, as shown in Fig. 11, in the same manner⁽⁶⁾ as done by Murakami *et al.* Using the area and the value of H_v in Table 3, the fatigue limit can be predicted according to Eq. (1). The predicted fatigue limits are shown in Table 5. It is said that the values are sufficiently valid, according to the results of fatigue tests shown in Figs. 6 and 7.

The predicted fatigue limits of low-temperature-tempered specimens are nearly the same as those of high-temperature-tempered specimens. Therefore, it is said that the low-temperature-tempering is not necessarily effective as a method of improving the fatigue strength of low-alloy steel used for a long time under a cyclic stress.

Table 4 Maximum sizes (μm) of defects observed at the fracture origins

SCM435		SNCM439	SCM420	SNCM420
A	B			
38	36	46	93	70

Fig. 10 An example of fish-eye-type fracture in low-temperature-tempered steel (The inclusion is adjacent to the specimen surface)

4.2 Carburized steels

In general, formation of surface structure anomalies (internal oxides and nonmartensitic structures) is inevitable for low-alloy steel carburized in generated gas, and it is well known that the surface structure anomalies cause^{(3),(4)} the reduction of fatigue strength. When the surface structure anomalies were removed by grinding off from the as-carburized specimens, the fatigue strengths were improved, as shown in Figs. 8 and 9. The S-N curves, however, dropped linearly even in the long life range over 10^7 cycles, and no fatigue limits were found up to about 10^9 cycles. Then, most of the fatigue fractures became fish-eye-type fractures (see mark *f* in Figs. 8 and 9). These phenomena were similar to the case in the long life range of low-temperature-tempered steels described above, but the fracture origins were observed at a depth of about 1.0 mm because of both high hardness and residual compressive stress near the specimen surface.

Thus, the prediction of fatigue limit of ground-off specimens will be attempted, using the following equation⁽⁶⁾ proposed by Murakami *et al.* for the prediction of fatigue limit of steel with subsurface microdefects and Eq. (1) given above.

$$\sigma'_w = 1.56(H_v + 120)/(\sqrt{\text{area}})^{1/6}, \quad (2)$$

where σ'_w (MPa) is the fatigue limit at the location of the defect, while H_v and $\sqrt{\text{area}}$ are the same as in Eq. (1).

At the fracture origins of ground-off specimens, fracture surfaces of intergranular and/or anomalistic microstructure are observed in addition to nonmetallic inclusions, as shown in Fig. 12. Although the mechanisms of formation are still unknown, these, like inclusions, will be deemed subsurface microdefects in the following discussions.

It is assumed that spherical defects, whose diameters are equal to the maximum value (see Table 4) of sizes of defects observed at the fracture origins, exist

Table 5 Predicted fatigue limits (MPa)

SCM435		SNCM439	SCM420	SNCM420
A	B			
511	534	520	606	647

Fig. 11 Area of defect that is adjacent to specimen surface

(a) The intergranular fracture surface observed at the fracture origin

(b) The fracture surface of anomalous structure observed at the fracture origin

Fig. 12 Examples of fracture surface near fracture origin of fish-eye-type fracture in carburized steel (in addition to inclusion)

at intervals of 0.1 mm from the specimen surface toward the internal direction. The area of maximum section of the assumed spherical defect is employed as the area in Eq. (2). On the other hand, the area in Eq. (1) is taken as shown in Fig. 11. The values of H_v are determined from the hardness distributions shown in Fig. 1.

Using these values, the fatigue limit distributions can be predicted according to Eqs. (1) and (2). The predicted fatigue limit distributions are shown in Fig. 13. According to the applied bending stress distributions (solid lines in Fig. 15) adjacent to the predicted fatigue limit distributions, 606 MPa and 647 MPa are obtained as the predicted values of fatigue limits for the SCM 420 and the SNCM 420 ground-off specimens, respectively. On the basis of the results shown in Figs. 8 and 9, these values can be said to be sufficiently valid.

The predicted fatigue limits of ground-off specimens are not substantially different from the fatigue limits obtained in the as-carburized specimens. Consequently it is said that the elimination of surface structure anomalies is not very effective as a method of improving the fatigue strength of carburized steel used for a long time under cyclic loading. On the other hand, only the ground-off specimen to which cyclic stress of 1 060 MPa was applied did not fail up to 3.5×10^8 cycles (see Fig. 8), though the applied cyclic stress was higher than the predicted fatigue limit (606 MPa). This is presumably due to a lack of defects that may become fracture origins. In such a case, fatigue limit nearly proportional to the hardness can be expected, but this should be considered an exceptional case.

It has already been reported⁽³⁾⁽⁴⁾ that the fracture surface features at the fracture origin of an as-car-

Fig. 13 Predicted fatigue limit distributions and applied bending stress distributions in carburized steels

burized specimen correspond very well to the presence of two knees recognized in the S-N diagram. Similar tendencies were also found in this study. That is, in the short life range up to the first knee, an intergranular fracture surface is observed at the fracture origin, followed by a transgranular fracture surface reflecting the microstructure (fracture surface in stage 2 a) as shown in Fig. 14(a). Since internal oxides could be seen on the intergranular fracture surface, it is clear that the intergranular fracture occurred along the internal oxides. In the long life range over the second knee, on the other hand, a featureless facetlike fracture surface⁽³⁾ is observed instead of a transgranular fracture surface as shown in Fig. 14 (b). The difference in such a fracture surface at the fracture origin was also added to each test point in Figs. 8 and 9.

When fatigue tests of as-carburized specimens

(a) in the short range ($<10^5$ cycles) (b) in the long life range ($>10^6$ cycles)

Fig. 14 Examples of fracture surface near fracture origin in carburized steel with surface structure anomalies (in the case tested in laboratory air)

were carried out in dry air, no featureless facetlike fracture surfaces were observed after the intergranular fracture surfaces and the fracture origins in the long life range over 10^6 cycles shifted from surface to subsurface, as shown in Figs. 8 and 9. Also, the fatigue strengths became higher than those in laboratory air and coincided with those of ground-off specimens tested in laboratory air. On the other hand, the as-carburized specimens tested in laboratory air had the fatigue limits, though the values were markedly low (see Figs. 8 and 9). Then, it has been reported⁽³⁾ that the size of the featureless facetlike fracture surface increased with decreasing applied cyclic stress. Consequently, it is presumed that the featureless facetlike fracture surfaces observed in laboratory air were formed by the interaction between corrosion due to moisture in air and mechanical crack growth due to cyclic stress, and it is concluded that this time-dependent type fracture induced the occurrence of the second knee and the reduction of fatigue strength in as-carburized specimens with surface structure anomalies.

5. Conclusions

Rotating bending fatigue tests of JIS SCM 435 and SNCM 439 steels tempered at low temperatures ($150\sim 200^\circ\text{C}$) or JIS SCM 420 and SNCM 420 steels carburized in generated gas were conducted in laboratory air and dry air, with particular attention paid to the long life range over 10^7 cycles and the influence of moisture in air. The experimental results were investigated from the standpoint of these fractographies and the equations proposed by Murakami *et al.* for the prediction of fatigue limit with microdefects. The following conclusions have been obtained.

(1) In the case of low-temperature-tempered

steels: (a) The S-N diagrams revealed two knees on the curves, which dropped linearly even over 10^7 cycles, and no fatigue limits were found up to 10^9 cycles. (b) These phenomena resulted from the inclusions within the steels, which became the fracture origins. (c) The values ($510\sim 530$ MPa) of fatigue limits predicted for the specimens tempered at low temperatures were not substantially different from the values ($480\sim 580$ MPa) of fatigue limits obtained for the specimens tempered at high temperature (600°C). (d) No influence of moisture in air was recognized in the fatigue strength characteristics.

(2) In the case of carburized steels: (a) The S-N diagrams of as-carburized specimens with surface structure anomalies revealed three knees on the curves; the fatigue limits were found over 10^8 cycles, and the values ($500\sim 600$ MPa) were nearly the same as those ($480\sim 580$ MPa) of high-temperature tempered SCM 435 and SNCM 439 steels. (b) Although the fatigue strengths of ground-off specimens without surface structure anomalies were improved, both knees and fatigue limits in the S-N diagrams were not found up to 10^9 cycles. (c) The values ($600\sim 650$ MPa) of fatigue limits predicted for the ground-off specimens were not substantially different from the experimental values ($500\sim 600$ MPa) of fatigue limits obtained for the as-carburized specimens. (d) The influence of moisture in air was recognized in the long life range of as-carburized specimens, and it is presumed that the occurrence of the second knee and the reduction of fatigue strength were induced by the interaction between corrosion due to moisture in air and mechanical crack growth due to cyclic stress.

(3) From (1)-(c), (2)-(a) and (2)-(c) mentioned above, it can be said that neither low-temperature tempering nor carburizing should be

expected to yield good results as a method of improving fatigue strength of low-alloy steel used for a long time under cyclic loading.

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