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1 Introduction

In almost all cases, the hot rolled sheet steels used conventionally in automobile wheels and other parts of the chassis have been materials with a strength level of TS 590 MPa grade or under.[1-5] However, in response to the heightened demand for reduced auto body weight with the aims of improving fuel economy and reducing CO_2 emissions, which have been required in recent years from the viewpoint of protection of the global environment, the development of a 780 MPa grade high strength hot rolled sheet steel for use in these applications has been desired.

Sheet steels for use in chassis parts must provide satisfactory properties in various respects, including press formability, shape fixability, fatigue strength, and weldability. In particular, in auto wheels and other parts of the chassis, fatigue strength is important in notched parts which are made by piercing or similar processes.

Conventional high strength hot rolled sheet steels with TS exceeding 590 MPa are broadly classified into two types, depending on the method of strengthening, these being the transformation hardened type and the precipitation hardened type. However, with the TS 780 MPa grade, it has been difficult to meet fatigue strength requirements with steels using either of these strengthening methods.

Against the above background, research on new microstructure control technologies aimed at solving these problems was carried out at Kawasaki Steel,[6,7] and a high strength hot rolled sheet steel suitable for auto wheels and other chassis parts was developed. This paper describes the results of research in connection with a new microstructure control technology for improving fatigue strength and the features of the 780 MPa grade hot rolled sheet steel which is produced based on those results.

2 Metallurgical Factors Governing Fatigue Strength of High Strength Hot Rolled Sheet Steels

2.1 Effect of Ferrite Precipitation Hardening on Fatigue Strength

It is known that fatigue strength increases as tensile strength increases. Abe et al.[8] and Kurita et al.[9] have reported that high fatigue strength can be obtained by solution/precipitation hardening, which directly strengthens the ferrite phase of ferrite-bainite structure steels. Moreover, reports[10,11] that fatigues strength is improved by strain induced transformation of retained

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Table 1 Chemical composition, structure and mechanical properties of steels

	Chemical composition (mass%)				Structure	Volume fraction of ferrite (%)	Grain size of ferrite (μm)	YS (MPa)	TS (MPa)	El (%)
	C	Si	Mn	Ti						
A	0.07	1.53	1.84	—	F+B+M	89	9.9	419	592	33
B	0.08	1.54	1.83	0.05	F+B+M	89	8.5	427	711	25
C	0.08	1.53	1.79	0.11	F+B+M	91	7.5	496	772	22
D	0.08	1.54	1.81	0.15	F+B+M	93	7.5	585	808	21
E	0.08	0.68	1.09	—	F+P	91	9.2	373	496	39
F	0.08	0.69	1.09	0.03	F+P	93	6.8	485	573	31
G	0.08	0.68	1.09	0.06	F+P	95	6.4	564	644	28

F: Ferrite, B: Bainite, M: Martensite, P: Pearlite

Table 2 Chemical composition, structure and mechanical properties of steels

	Chemical compositon (mass%)						Structure	Volume fraction of ferrite (%)	YS (MPa)	TS (MPa)	YR	El (%)
	C	Si	Mn	Ti	Nb	Cr						
H	0.08	1.61	1.73	0.10	—	—	Precipitated F+M	81	507	787	0.64	21
I	0.11	1.60	1.55	—	—	1.02	F+M	60	433	864	0.50	21
J	0.11	0.43	1.50	0.16	0.04	—	Precipitated F+B+M	72	679	782	0.87	17

austenite have mentioned that the second phase also has a large effect on fatigue strength. On the other hand, it is also reported[13] that martensite is less effective than ferrite in improving fatigue strength. Thus, as can be seen from the above, there has been no unified interpretation of the optimum structure for obtaining high fatigue strength.

Therefore, in order to clarify the influence of precipitation hardening and the second phase on the fatigue characteristics of low carbon steel having ferrite as the major phase, the authors investigated fatigue strength and fatigue crack propagation characteristics using a vacuum melted research steel.

2.2 Samples and Experimental Procedure

The chemical composition, mechanical properties, microstructure, volume fraction of ferrite, and grain size of ferrite of the sample materials which were used to investigate fatigue strength are shown in **Table 1**.

Steels A-D have a major phase of ferrite (F) and a minor phase of bainite (B) + martensite (M). The degree of precipitation hardening of these steels was varied by adjusting the Ti content. Steels E-G have a major phase of ferrite and a minor phase of pearlite (P). The degree of precipitation hardening was varied in the same manner, using the Ti content.

Specimens were taken parallel to the rolling direction, and were reduced to a thickness of 2.6 mm by grinding on both sides to eliminate the influence of surface roughness. The pieces were used in experiments after machining to the shape shown in **Fig. 1** (a).

Fatigue tests were performed by completely reversed plane bending (stress ratio, $R = -1$) with a schenck type plane bending fatigue test device. Bending was repeated at a speed of 20 Hz. The fatigue limit σ_w, is the stress at

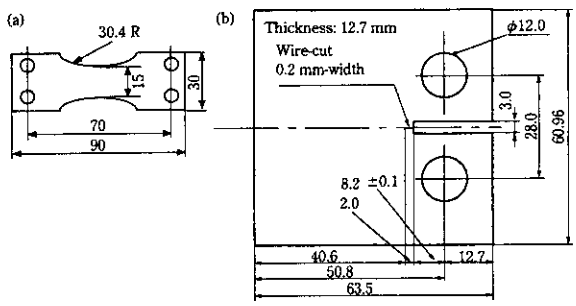

Fig. 1 Shape and size of fatigue test specimen; (a) Plane bending test specimen, (b) Fatigue crack propagation test specimen

which failure does not occur after repeated bending for 10^7 cycles. The value of this fatigue limit was used as the fatigue strength in this paper.

Next, fatigue crack propagation characteristics were investigated using steels having the chemical composition, mechanical properties, and structure shown in **Table 2**. Specimens were taken parallel to the rolling direction, reduced to a thickness of 12.7 mm by grinding on both sides, and used in the experiments after machining to the shape shown in Fig. 1 (b). Tests of the propagation of fatigue cracks were performed with an electric oil hydraulic type fatigue test device under a sine wave load with a stress ratio of $R = 0.05$. A ΔK graded increase test with a constant stress amplitude was then performed, the length of cracks was measured by the compliance method, and the crack propagation rate and stress intensity factor range (ΔK) were obtained.[14]

2.3 Experimental Results

The results of plane bending fatigue tests of steels A-

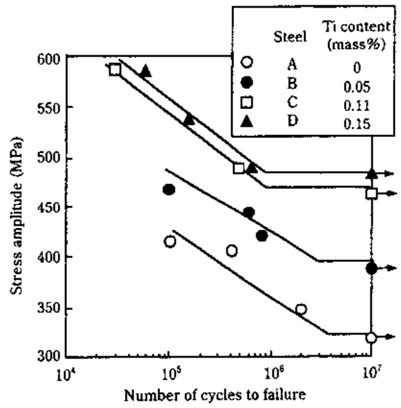

Fig. 2 Relationship between stress amplitude and number of cycles to failure in ferrite-bainite-martensite steel

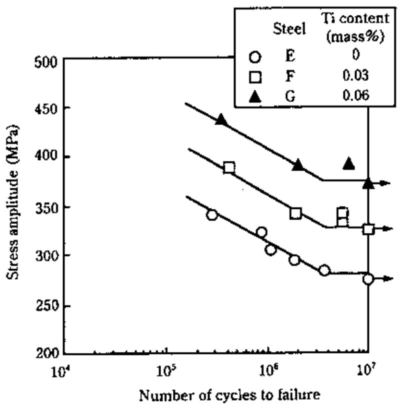

Fig. 3 Relationship between stress amplitude and number of cycles to failure in ferrite-pearlite steel

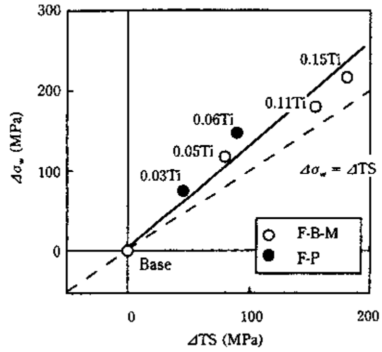

Fig. 4 Effect of titanium content on increase of fatigue strength ($\Delta\sigma_w$) and increase of tensile strength (ΔTS)

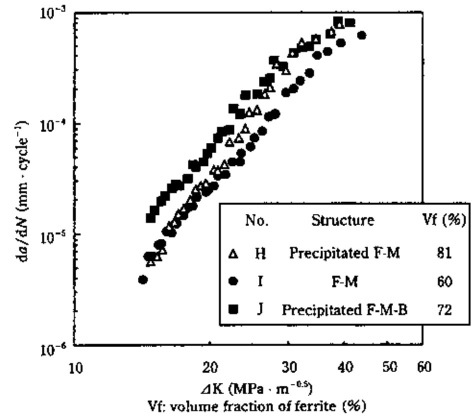

Fig. 5 Relationship between stress intensity factor range (ΔK) and fatigue crack propargation rate (da/dN) in ferrite-martensite and ferrite-martensite-bainite steels

D, which have a major phase of ferrite (F) and a minor phase of bainite (B) + martensite (M) are shown in **Fig. 2**. The results for steels E-F, which have a major phase of ferrite (F) and a minor phase of pearlite (P), are shown in **Fig. 3**. The relationship between the increment of tensile strength, ΔTS, due to Ti addition and the increment of the fatigue limit, $\Delta\sigma_w$, indexed to a steel without Ti as a base, is shown in **Fig. 4**. In both the F-M-B steels and the F-P steels, the increase in fatigue strength which accompanies increases in the Ti content is greater than the increment of tensile strength. Accordingly, precipitation hardening of the ferrite phase by Ti is effective in increasing fatigue strength, even when the minor phase is either bainite + martensite or pearlite.

The relationship between the fatigue crack propagation rate (da/dN) and the stress intensity factor range (ΔK) of the F-M (PF-M) steel H and F-M steel I, both of which have precipitation hardened structures, and the precipitation hardened F-M-B (PF-M-B) steel J, is shown in **Fig. 5**. In comparison with the PF-M-B steel J, the F-M steel I has a small crack propagation rate. The PF-M steel H shows approximately the same crack propagation rate as steel I in the range where ΔK is small, but the crack propagation rate becomes the same as that of steel J as ΔK increases.

2.4 Discussion

According to Abe et al.,[8] fatigue properties are not characteristics which can be assigned a direct relationship to static strength properties such as yield strength and tensile strength, and it is therefore assumed that fatigue properties must essentially be classified and studied by the type of strengthening mechanism. Considering this point, the authors investigated the improvement of tensile strength and fatigue strength in the present research.

First, the contribution of precipitation hardening to fatigue strength was examined. In sample steels A-G, the fraction of the ferrite phase was virtually unchanged in the respective structures with a major phase of ferrite

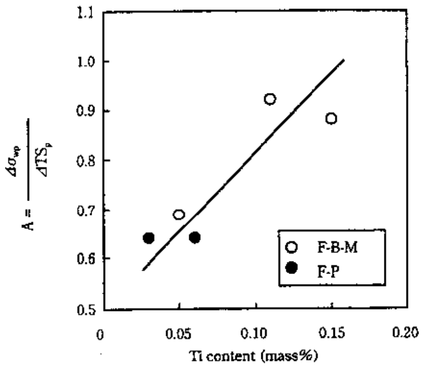

Fig. 6 Effect of titanium content on ratio of increase of fatigue strength ($\Delta\sigma_{wp}$) to that of tensile strength (ΔTS_{wp})

(F) and a minor phase of bainite (B) + martensite (M) and a major phase of ferrite and a minor phase of pearlite (P). Therefore, there is no problem in assuming that the influence of the content of the minor phase can be ignored. Accordingly, fatigue strength can be divided into the contribution of precipitation hardening attributable to Ti and the contribution of grain refinement hardening of the ferrite grains, and changes in fatigue strength can be estimated using Eq. (1)

$$\Delta\sigma_w = \Delta\sigma_{wp} + \Delta\sigma_{wg} = A\Delta TS_p = B\Delta TS_g \cdots (1)$$

Here, $\Delta\sigma_{wp}$: increase in σ_w due to precipitation hardening, $\Delta\sigma_{wg}$: increase in σ_w due to grain refinement hardening, ΔTS_p: increase in TS due to precipitation hardening, ΔTS_g: increase in TS due to grain refinement hardening, A, B: constants.

The amount of increase in tensile strength, ΔTS_g due to grain refinement hardening can be expressed by the Hall-Petch equation, as shown in Eq. (2)

$$\Delta TS_g = K\Delta d^{-1/2} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

K is a constant. Here, the value of 17 $Nmm^{-3/2}$, which Pickering[15] measured with carbon steel, is used. As the constant B, which expresses the contribution of grain refinement hardening, a value of $B = 0.5$, which is in the range of past research,[8,9] is used. **Figure 6** shows the results of calculations of A, which is a constant expressing the contribution of precipitation hardening to fatigue strength in the respective structures of F-M-B and F-P using the fatigue strength in the present research, based on the hypotheses mentioned above. As the content of added Ti increases, the constant A also increases. According to Prenosil,[16] it has been reported that fine precipitates redissolve under repeated stress, and consequently, repetition resistance is reduced. Thus, it is considered that the reason why the constant A, which expresses the contribution of precipitation hardening to fatigue strength, increases as the amount of Ti addition increases is because this redissolution becomes difficult due to coarsening of the precipitates.

Next, the difference in the fatigue crack propagation rates of sample steels H-I were investigated. It has been reported[17-19] that the propagation of fatigue cracks is arrested by a hard minor phase in steels with a complex structure. Accordingly, it is considered that the crack propagation rate is small in the F-M steel I which, in comparison with the PF-M-B steel J, has a harder minor phase and a large minor phase fraction. On the other hand, the fact that the fatigue crack propagation rate of steel H, which has a smaller minor phase than steel J, is virtually the same as that of steel I in the range where ΔK is small is considered to be because steel H has a simple phase of hard martensite as the minor phase.

Fatigue characteristics can generally be divided into the initiation of fatigue cracks and the progress (propagation) of fatigue cracks. Fatigue strength is improved when Ti or another precipitation element is used to strengthen the ferrite phase, which is soft in comparison with the minor phase, because the former characteristic, namely, crack initiation, is suppressed. Moreover, the propagation of cracks which have occurred can be suppressed by creating a minor phase of harder martensite, further improving fatigue strength.

3 Concept of Manufacture of 780 MPa Grade Hot Rolled Sheet Steel with High Fatigue Strength

As described above, it has become clear that fatigue strength is markedly improved by adopting a complex structure composed of a ferrite phase and a martensite phase and causing precipitation hardening of the ferrite phase. Furthermore, in addition to fatigue characteristics, improvement of the following properties can also be expected.

(1) Causing precipitation hardening of the ferrite phase reduces the difference in strength between the ferrite phase and the hard martensite phase. This in turn reduces the concentration of strain in the ferrite phase, and thus increases local elongation, resulting in improved stretch flanging formability.

(2) The advantages of a low yield point and uniform elongation provided by dual-phase type, complex structure steels can be secured.

(3) A happy medium can be obtained in the weld hardening property, in that welds do not show abnormal hardening, as in the case of transformation hardened steels, and welding does not cause softening of the HAZ, as in the case of precipitation hardened steels.

The main point with regard to the manufacturing conditions which are required in hot rolling in order to create the structure described above in hot rolled steel sheets with 780 MPa class tensile strength is to apply conditions which will promote the following two reactions in the cooling process, where the austenite-to-ferrite transformation occurs after hot rolling. The first is a condition under which fine TiC, which is a factor in pre-

Table 3 Chemical composition of newly developed 780 MPa TS grade steel

(mass%)

C	Si	Mn	Ti	P	S	Al
0.08	1.50	1.80	0.10	0.010	0.001	0.030

Table 4 Mechanical properties of newly developed 780 MPa TS grade steel

Thickness (mm)	YS (MPa)	TS (MPa)	El (%)
3.2	653	816	24
4.5	638	832	22
6.0	659	834	22

cipitation hardening, will precipitate promptly in the ferrite grains immediately after the austenite-to-ferrite transformation; the second is a condition in which the excess C that was not consumed to form TiC is made to segregate to the austenite phase side which exists at this point in time, and the formation of martensite in the subsequent cooling process is facilitated. Chemical composition and cooling conditions play important roles in stably securing these conditions. First, it is necessary to cause the precipitation nose of TiC to coincide with the nose of the austenite-to-ferrite transformation. Therefore, in realizing the former condition, it is necessary to optimize the contents of Ti and C, and the contents of Si and Mn in order to expand the stable region of the dual phase condition of austenite + ferrite. In realizing the latter condition, it is important to control the cooling pattern so that the above-mentioned reaction in the dual phase condition progresses rapidly and efficiently during the short cooling period.

4 Features of Hot Rolled Sheet Steel

Based on the concept described above, the chemical composition and hot rolling and cooling conditions of 780 MPa grade high strength hot rolled sheet steel with high fatigue strength were optimized, and the newly developed steel was manufactured using the works hot rolling mill. **Table 3** shows the chemical composition of the new steel. **Table 4** shows the mechanical properties at various thicknesses. **Figure 7** shows the results of the relationship of the fatigue limits of machined specimens and notched specimens and the strength of the mother material in a flat bending fatigue test. In this figure, the newly developed steel is compared with conventional precipitation hardened steel and dual phase steel. With both the machined specimens and the notched specimens, the newly developed steel showed higher fatigue limit values than the precipitation hardened steel and dual phase steel. As was clear form the above-mentioned laboratory research results, the newly developed sheet steel shows excellent fatigue characteristics because the

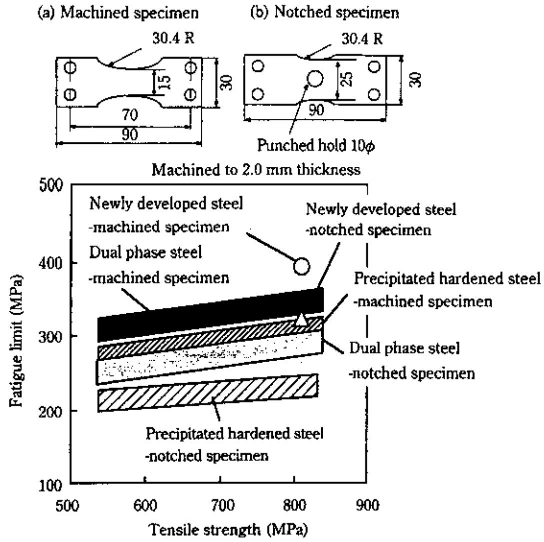

Fig. 7 Effect of microstructure and tensile strength on fatigue limit

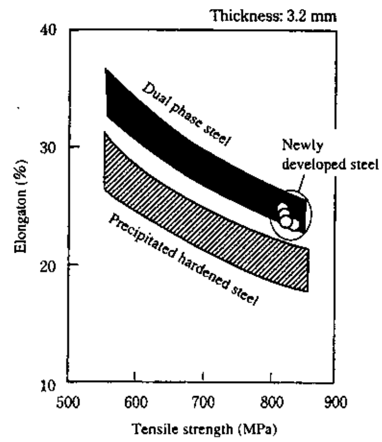

Fig. 8 Effect of microstructure and tensile strength on elongation

initiation of cracks is deterred by precipitation hardening of ferrite, and the propagation of cracks is suppressed by martensite.

Figure 8 shows the results of a comparison of the tensile strength-elongation balance of the newly developed steel and the conventional precipitation hardened steel and dual phase steel. The tensile strength-elongation balance of the new steel is superior to that of the conventional precipitation hardened steel and equal to that of the dual phase steel. This is because the newly developed steel is a steel with a complex structure of the same type as the dual phase steel.

Figure 9 shows the relationship between tensile strength and the hole expanding ratio. The hole expanding property of the newly developed steel is superior to that of both the dual phase steel and the precipitation

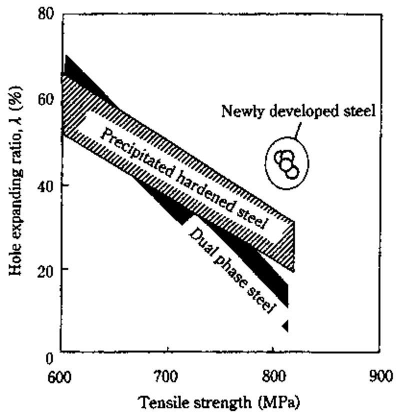

Fig. 9 Effect of microstructure and tensile strength on hole expanding ratio, λ

hardened steel. This is because precipitation strengthening of the ferrite phase had the effect of reducing the strength difference between the ferrite phase and the hard second phase of martensite, and thus suppressing concentrations of deformation in the ferrite grains during working.

5 Conclusion

The effect of microstructure on fatigue strength was investigated with the aim of developing a TS 780 MPa grade hot rolled sheet steel with high fatigue strength, which is suitable for automobile wheels and other parts of the chassis. The following conclusions were obtained.

(1) Even when the second phase is either bainite + martensite or pearlite, fatigue strength is improved by precipitation hardening of the main ferrite phase with Ti. This is because further strengthening of the ferrite phase, which is soft in comparison with the second phase, suppresses the initiation of fatigue cracks.

(2) It is possible to suppress the propagation of cracks which have occurred by creating a single phase of martensite, which is a harder phase, as the second phase, thus realizing a further increase in fatigue strength.

(3) The new 780 MPa grade hot rolled sheet steel has a complex structure consisting of a ferrite phase and a martensite phase, and precipitation hardening is applied to the ferrite phase. The new steel has high fatigue strength and shows an excellent strength-elongation balance and high hole expansion ratio in comparison with conventional steels.

Base on the knowledge described above, which was obtained in the laboratory, the chemical composition and hot rolling and cooling conditions were optimized. The newly developed high strength hot rolled sheet steel was applied to ultra-high strength, lightweight wheels using TS 780 MPa grade high strength sheet steel for the first time in the world.[20] These wheels achieve a weight reduction of approximately 10% in comparison with wheels of TS 590 MPa grade high strength steel. This percentage of weight reduction has a sufficient effect to justify replacing steel wheels with aluminum. Furthermore, the fatigue life of these wheels has been improved by approximately 20%, also contributing to improved product reliability. For the future, application to the chassis and other auto components is also being studied, and is expected to have a similar effect to that in the case of wheels.

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