Effects of Strengthening Mechanisms on Fatigue Properties of Ferrite–Pearlite Hot-rolled Sheet Steel

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The purpose of this study is to clarify the effects of strengthening mechanism on the fatigue properties of ferrite plus pearlite sheet steel. Ferrite plus pearlite sheet steels having the tensile strength of 400 to 600 MPa grade were prepared with being strengthened by solid solution, precipitation, increased dislocation density, grain-refinement or increased pearlite volume fraction. Furthermore, a ferrite plus bainite steel was prepared to investigate the effect of replacement of the second phase pearlite with harder phase, bainite. Load-controlled fatigue test and strain-controlled fatigue test were carried out to examine fatigue limits and obtain cyclic stress response curves, respectively.

Main results are as follows: (1) The ratio of an increase in fatigue limit to an increase in tensile strength ($\Delta\sigma_w/\Delta\sigma_B$) heavily depended on strengthening mechanism. The ratio was higher for both solid solution and precipitation strengthenings than bainite or grain-refinement strengthenings, while lower for dislocation and pearlite strengthenings. (2) Stress amplitude obtained from cyclic stress response curve related more closely to fatigue limit than to tensile strength. (3) The initial fatigue cracks were observed only in the ferrite matrix; but not in the second phase. (4) It was concluded from these results that it is of vital importance to strengthen the ferrite matrix itself by solid solution or precipitation in order to obtain higher ratio of $\Delta\sigma_w/\Delta\sigma_B$.

KEY WORDS: hot rolled sheet steel; ferrite plus pearlite structure; strengthening mechanism; fatigue limit; solid solution; precipitation; dislocation density; volume fraction of pearlite; grain refinement.

1. Introduction

Reduction of automobile weight has recently been demanded for fuel economy and environmental preservation. To satisfy this request, thinner gauged hot-rolled steel sheets should be used and also the steel should have higher tensile strength considering fatigue strength of underbody parts such as lower arm, wheel disc and wheel rim. Increasing of tensile strength, however, generally leads to poor formability, and may cause breakage, necking, or other problems during press-forming. Therefore increasing of endurance ratio of hot-rolled sheet steel, which is the ratio of fatigue limit to tensile strength, is of vital importance.

Some studies have clarified that fatigue properties depend not only on the mechanical properties such as tensile strength and hardness, but also on the chemical composition and the microstructure. The effects of precipitation strengthening elements,¹⁾ solid solution strengthening elements,²⁾ and dual phase microstructure,³⁾ on fatigue properties have been intensively investigated. Those studies showed that controlling of chemical composition and microstructure could bring about an increase in the endurance ratio. But few previous studies have yet provided systematic and qualita-

tive information on the relationship between fatigue properties and metallurgical factors.⁴⁾

The objective of this paper is to clarify qualitatively and systematically the effect of strengthening mechanism on the fatigue limit and cyclic stress response and to provide guidelines on developing of high strength steel with a higher endurance ratio.

2. Experimental Procedure

2.1. Materials

Chemical compositions, and rolling and cooling conditions are given in **Table 1**. All materials are low carbon sheet steel with approximately 6 mm in thickness. All of them were obtained by hot rolling simulation in laboratory.⁵⁾ The base material is 0.15C–1.2Mn steel having tensile strength of approximately 450 MPa. Thirteen kinds of materials are strengthened to the base material with various mechanisms, aiming at the tensile strength of 500 to 600 MPa.

For solid solution (S.S.) strengthening, silicon (0.5 mass%, 1.0 mass%), phosphorus and nitrogen—low temperature coiling was applied to suppress AlN precipitation⁶⁾—were added separately. For precipitation strengthening, vanadium, niobium or titanium was

Table 1. Chemical compositions and rolling conditions.

Steel		chemical compositions (mass%)							rolling conditions		
		C	Si	Mn	P	S	Al	N	Others	FT	SCT
Base		0.14	0.05	1.19	0.021	0.002	0.040	0.0026		1093	AC 873
Solid Solution	Si(0.5%)	0.15	0.54	1.22	0.021	0.002	0.040	0.0021		1093	AC 873
	Si(1.0%)	0.14	0.93	1.20	0.025	0.002	0.038	0.0022		1093	AC 873
	P	0.14	0.05	1.19	0.065	0.002	0.034	0.0025		1093	AC 873
	N	0.15	0.05	1.23	0.026	0.002	0.033	0.0270		1093	AC 673
Precipitation	VN	0.15	0.05	1.22	0.022	0.002	0.034	0.0190	V :0.100	1093	AC 873
	Nb(CN)	0.14	0.05	1.20	0.022	0.002	0.037	0.0037	Nb:0.040	1093	AC 873
	TiC	0.15	0.05	1.17	0.020	0.002	0.033	0.0024	Ti:0.049	1093	AC 873
Dislocation		0.14	0.05	1.19	0.021	0.002	0.040	0.0026		973	AC 873
Grain Size	Fine	0.14	0.05	1.19	0.021	0.002	0.040	0.0026		1093	WS 873
	Coarse	0.14	0.05	1.19	0.021	0.002	0.040	0.0026		1193	AC 873
Pearlite	High C	0.25	0.05	1.20	0.019	0.002	0.033	0.0028		1093	AC 873
	Low C	0.05	0.05	1.21	0.021	0.002	0.033	0.0029		1093	AC 873
Bainite		0.15	0.00	1.43	0.016	0.001	0.045	0.0031		1153	WS 723

FT :Finish-rolling temperature (K)

SCT:Simulated coiling temperature (K)

Table 2. Mechanical properties.

Steel		σ_Y	σ_B	El.
Base		304	444	39.3
Solid Solution	Si(0.5%)	366	532	31.9
	Si(1.0%)	402	564	30.5
	P	320	476	34.2
	N	413	549	27.7
Precipitation	VN	474	601	25.2
	Nb(CN)	416	543	27.1
	TiC	440	543	29.3
Dislocation		363	509	25.9
Grain Size	Fine	306	460	33.1
	Coarse	287	441	37.1
Pearlite	High C	335	511	33.0
	Low C	279	402	39.9
Bainite		383	526	35.4

 σ_Y :yield strength(MPa) σ_B :tensile strength(MPa)

El.:elongation(%)

added separately. Dislocation and grain-refinement strengthened steels were obtained by using coupon slabs of the base material. For dislocation strengthening, one of the coupon slabs was finish-rolled at a lower temperature than $A_{r3}(=1087\text{K})$ to produce high-density dislocations in ferrite grains. For grain-refinement strengthening, another slab was rapidly cooled after finish-rolling. For comparison, another slab was finally rolled at a higher temperature to promote grain coarsening. For pearlite strengthening, carbon was added to the base material to increase the volume fraction of pearlite and as a comparison, carbon was reduced to decrease the volume fraction of pearlite.

All of these materials had ferrite plus pearlite structure. As a comparison of ferrite plus pearlite structure, the material having ferrite plus bainite structure was prepared by a combination of rapid cooling and low temperature coiling. The chemical composition was chosen close to the base material. This will clarify the effect of second hard phase on fatigue properties.

Mechanical properties are listed in **Table 2**. Microstructures and microstructural characteristics are shown in **Fig. 1** and in **Table 3**, respectively.

Fig. 1. Optical microstructures.

- 1) Base 2) Si(0.5%)-S.S. 3) Si(1.0%)-S.S. 4) P-S.S.
- 5) N-S.S. 6) V-precipitation 7) Nb-precipitation 8) Ti-precipitation 9) Dislocation 10) Grain size (fine)
- 11) Grain size (coarse) 12) Pearlite (high C) 13) Pearlite (low C) 14) Bainite

Table 3. Microstructural characteristics.

Steel		d	Vf
Base		13.8	12
Solid Solution	Si(0.5%)	11.7	21
	Si(1.0%)	11.0	15
	P	15.7	17
	N	11.5	15
Precipitation	VN	9.6	5
	Nb(CN)	7.9	14
	TiC	8.8	5
Dislocation		9.7	12
Grain Size	Fine	7.6	10
	Coarse	23.9	18
Pearlite	High C	15.2	24
	Low C	13.6	4
Bainite		6.9	11

d: average grain size (μm)

Vf: volume fraction of the second phase (%)

Fig. 2. Size of fatigue test specimen.

2.2. Test Specimen

The test specimen is illustrated in **Fig. 2**. The rolling direction of steel sheets was chosen parallel to the axial loading direction of the specimens. The surface of the specimen was mechanically polished by using #700 emery paper in the axial direction to remove any circumferential scratches and machine marks.

2.3. Fatigue Tests

2.3.1. Load-controlled Fatigue Test

Load-controlled fatigue test was carried out to examine the fatigue limit. The testing machine had an electro hydraulic servo controlled system. Fatigue test was performed at a stress ratio of -1 and frequencies of 15 to 20 Hz.

2.3.2. Strain-controlled Fatigue Test

Strain-controlled fatigue test was carried out to obtain cyclic stress response curve, which indicates the resistance of the material against cyclic deformation. The same testing machine referred to in the previous section was employed and fatigue test was performed at a strain ratio of 0 and frequencies of 2 to 4 Hz. The strain ratio was chosen so as to ensure that it would not buckle under compressive strain. The strain was monitored with a 12.5 mm extensometer which was attached to the gauge section of the test specimen.

3. Results

3.1. Load-controlled Fatigue Test

Relationship between stress amplitude and the number of cycles to failure is shown in **Fig. 3**. Fatigue limit (σ_w) was defined as the stress amplitude at which the test specimen fails at 10^7 cycles. σ_w and the endurance ratio

Fig. 3. Relationship between stress amplitude σ_a and the number of cycles to failure N_f .**Table 4.** Results of fatigue test.

Steel		σ_w	σ_w / σ_B	$\Delta\sigma_w / \Delta\sigma_B$
Base		198	0.45	—
Solid Solution	Si(0.5%)	285	0.54	0.99
	Si(1.0%)	314	0.56	0.97
	P	235	0.49	1.16
	N	288	0.53	0.86
Precipitation	VN	340	0.57	0.90
	Nb(CN)	304	0.56	1.07
	TiC	296	0.55	0.99
Dislocation		219	0.43	0.32
Grain Size	Fine	211	0.45	0.47*1
	Coarse	202	0.46	
Pearlite	High C	225	0.44	0.19*2
	Low C	204	0.51	
Bainite		250	0.48	0.63

*1: $\Delta\sigma_w$ and $\Delta\sigma_B$ is calculated by using "Fine" and "Coarse" steels

*2: $\Delta\sigma_w$ and $\Delta\sigma_B$ is calculated by using "High C" and "Low C" steels

Fig. 4. Relationship between tensile strength σ_B and fatigue limit σ_w .

Fig. 5. Changes in stress amplitude with the number of cycles under strain control ($\Delta\epsilon_t = 0.6\%$).

(σ_w/σ_B) are listed in Table 4. The relationship between σ_B and σ_w is shown in Fig. 4.

All of the precipitation strengthening materials with almost the same σ_B , exhibited a high endurance ratio of approximately 0.55. For S.S. strengthening, the endurance ratio increased almost proportionally with an increase of σ_B from the base irrespective of alloying element and exhibited the highest value of 0.56 for 1.0% Si steel with the highest σ_B . In contrast to S.S. and precipitation strengthenings, pearlite, grain-refinement, dislocation and bainite strengthenings exhibited a low endurance ratio of approximately 0.45.

3.2. Strain-controlled Fatigue Test

Changes in stress amplitude with the number of cycles under strain control ($\Delta\epsilon_t = 0.6\%$) were shown in Fig. 5. All materials exhibited cyclic softening. The stress amplitude in the beginning of the test was large nearly in the order of the yield stress shown in Table 2. The decrease of stress amplitude during fatigue test was larger in bainite and precipitation strengthenings than in Si

Fig. 6. Relationship between increase in tensile strength $\Delta\sigma_B$ and that in fatigue limit $\Delta\sigma_w$.

(1%) S.S. strengthening.

The fatigue test for $\Delta\epsilon_t = 0.3\%$ was also carried out. The results were nearly the same as those for $\Delta\epsilon = 0.6\%$.

4. Discussion

4.1. The Effects of Strengthening Mechanism on Fatigue Limit

Figure 4 shows that the endurance ratio of materials strengthened by Si S.S. depends on the amount of Si addition. Therefore the effects of strengthening mechanism should be discussed in terms of the ratio of increase of σ_w from the base material to that of σ_B , that is, $\Delta\sigma_w/\Delta\sigma_B$. Relationship between $\Delta\sigma_w$ and $\Delta\sigma_B$ is shown in Fig. 6 and the ratio $\Delta\sigma_w/\Delta\sigma_B$ is given in Table 4. Here the effect of strengthening mechanism on fatigue limit was summarized by using the equation

$$\sigma_w = \sigma_{w0} + A \cdot \Delta\sigma_B \quad (1)$$

where σ_{w0} denotes the fatigue limit of the base material and A is a constant, depending on the strengthening mechanism. In order to clarify the effects of various strengthening mechanisms, the constant A 's were evaluated. The constant A 's for S.S. strengthening were nearly the same high value irrespective of element and their average was about 0.99. The A 's for precipitation strengthening were also the same high value irrespective of element and their average was also about 0.99. For dislocation, the A is a low value of 0.32. For grain-refinement, the A was calculated to be 0.47 by using the values of difference in σ_B and σ_w between fine and coarse grained steels. For pearlite, the A was also calculated to be 0.17 by using the differential values between high carbon and low carbon steels. For bainite strengthening, the A was 0.63. These results indicate that S.S. and precipitation strengthenings are very effective in increasing the endurance ratio regardless of element but other strengthenings are ineffective.

The reason why the A changes markedly with strengthening mechanism was discussed. Fatigue crack is known to initiate in ferrite grains for ferrite-pearlite medium carbon steel.⁷⁾ As shown in Fig. 7 fatigue cracks and slip bands were also observed to initiate in ferrite

Fig. 7. SEM micrographs of surfaces of fatigue-tested specimens. P: Pearlite B: Bainite

1) Si (1%) solid solution	($\sigma_a = 353$ MPa, $N_f = 1.50 \times 10^5$)
2) Ti precipitation	($\sigma_a = 323$ MPa, $N_f = 8.20 \times 10^4$)
3) Bainite	($\sigma_a = 274$ MPa, $N_f = 1.35 \times 10^5$)

but not observed in the second hard phase pearlite or bainite. In addition, as shown in Fig. 6, the effect of volume fraction of pearlite on the fatigue limit was small in the carbon range from 0.05 to 0.25% investigated in this study. This result agrees with the reports^{7,8)} that the fatigue limit of S15C carbon steel was the same as that of S35C steel. The $\Delta\sigma_w/\Delta\sigma_B$ for pearlite strengthened steels is explained to be small because σ_B increases significantly with the volume fraction of pearlite but σ_w does not so much. It is concluded that the σ_w strongly reflects the resistance of ferrite against fatigue crack initiation.

From the above-mentioned discussion, strengthening of ferrite is more important to obtain a higher endurance ratio than that of the second hard phase such as pearlite or bainite. The ferrite strengthening mechanism was

classified into two types and discussed. One type is to increase the resistance against dislocation movement in the ferrite grain, such as S.S., precipitation and dislocation strengthenings. Dislocation strengthening, however, exhibited a lower value of A than two other strengthenings as shown in Fig. 6. Pre-strained sheet steels are known to exhibit cyclic softening under strain-controlled fatigue test⁹⁾ Thus dislocation structure formed at finish-rolling below A_{r3} is interpreted to be readily rearranged into being ineffective on fatigue limit under cyclic deformation in the present study.

The other type is grain refinement. Grain boundaries act as obstacles against crack propagation to neighboring grains. Therefore, strengthening by grain-refinement was thought to be effective in increasing the endurance ratio. And the relationship between grain size and fatigue limit is given in the following equation¹⁰⁾

$$\sigma_w = \sigma_0 + C \cdot d^{-0.5} \quad \dots\dots\dots (2)$$

where d is the grain size diameter. σ_0 is a constant which depends on the chemical composition and microstructure. And the C is also a constant of nearly 160 ($\sqrt{\mu\text{m}} \cdot \text{MPa}$). By using Eq. (2) the difference of fatigue limit between grain-refined and coarse-grained materials was calculated to be approximately 25 MPa. Considering this value it seems difficult to achieve a considerable high fatigue limit by grain-refinement in practice. As shown in Fig. 1 and Table 3, an addition of precipitation strengthening elements also results in grain-refinement. This indicates that the effect of precipitation element should be discussed by the two decomposed factors; precipitation and grain-refinement strengthenings. Contribution of grain-refinement to increasing of fatigue limit, however, is calculated to be at most 14 MPa. Therefore the most part of an increase in fatigue limit by precipitation element is considered to be caused by precipitation strengthening of ferrite.

It is concluded that increasing of the resistance of ferrite against cyclic dislocation movement by S.S. or precipitation strengthening is effective and useful practically in increasing the fatigue limit.

4.2. The Effects of Strengthening Mechanism on the Resistance against Cyclic Deformation

Stress amplitude (σ_a) under strain controlled fatigue test indicates the resistance of material against cyclic plastic deformation. It is reasonable for the σ_a to depend heavily on the microstructure formed during the cyclic deformation. Therefore σ_a is expected to relate to strengthening mechanism similar to that working in σ_w .

The relationships between σ_a and σ_B , or σ_w for both $\Delta\epsilon_t = 0.3\%$ and $\Delta\epsilon_t = 0.6\%$ are shown in Figs. 8 and 9. These figures indicate that σ_a relates more closely than to σ_B . The correlation coefficient of the relationship between σ_a and σ_w was higher than that of σ_a and σ_B . The correlation coefficient between σ_a and σ_w for $\Delta\epsilon_t = 0.6\%$ was 0.97 while that between σ_a and σ_B was 0.91.

Thus the relationship between σ_a and σ_w can be described in the following equation

Fig. 8. Relationship between tensile strength σ_B and stress amplitude σ_a for strain controls of 0.6 and 0.3%.

Fig. 9. Relationship between fatigue limit σ_w and stress amplitude σ_a for strain controls of 0.6 and 0.3%.

$$\sigma_w = \alpha \cdot \sigma_a + \beta \quad \text{.....(3)}$$

where α and β are constants depending on $\Delta\epsilon_t$. This indicates that the resistance of ferrite against dislocation movement during cyclic deformation directly relates to the resistance against fatigue crack initiation and propagation. This is also supported by a literature¹¹⁾ that the cyclic yield strength calculated by companion specimen method related to the fatigue limit.

It is concluded that in order to improve fatigue limit, it is of the most importance to select carefully the strengthening mechanism which increases ferrite resistance against cyclic dislocation movement.

5. Conclusions

In order to clarify the effects of strengthening mechanism on the fatigue properties of ferrite plus pearlite sheet steel, load-controlled fatigue test and strain-controlled fatigue test were carried out by using laboratory melted steels ranging of 400 to 600 MPa in tensile strength. Main results are as follows:

(1) Fatigue limit (σ_w) can be summarized in the following equation

$$\sigma_w = \sigma_{w0} + A \cdot \Delta\sigma_B$$

where σ_{w0} is the fatigue limit of the base ferrite pearlite steel and A is a constant denoting the ratio of an increment of fatigue limit ($\Delta\sigma_w$) to that of tensile strength ($\Delta\sigma_B$). The A has a different value for each strengthening mechanism; A is 0.99 for both solid solution and precipitation strengthenings, 0.63 for bainite transformation, 0.47 for grain-refinement, 0.32 for dislocation, and 0.19 for pearlite.

(2) Fatigue cracks were observed to initiate only in the ferrite matrix but not observed in the second hard phase of pearlite or bainite.

(3) Stress amplitude (σ_a) under strain-controlled fatigue test was found to relate more closely to σ_w than to σ_B . This suggests that the resistance of ferrite against cyclic movement of dislocation is directly related to resistance against fatigue crack initiation and propagation.

(4) It is concluded from the above test results that strengthening mechanisms such as precipitation and solid solution which contribute to resistance of the ferrite matrix against cyclic movement of dislocation should be carefully selected to obtain a higher endurance ratio (σ_w/σ_B).

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