Effect of Metallurgical Factors on Fatigue Properties in 5.5Ni-Cr-Mo-V Steel*

By Masae SUMITA** and Iku UCHIYAMA**

Synopsis

Martensitic structures or mixed structures of martensite and bainite with various prior austenitic grain sizes and volumes or sizes of precipitates are obtained by various heat treatments, using HY140 steels. HY180 and 12%Ni maraging steels are also used. The effect of metallurgical factors on cycles to failure, on a crack growth rate, and on a cyclic stress-strain behaviour is examined and discussed. The results are as follows:

(1) Fatigue strength at 10^5 cycles increases with increase of cyclic yield strength and decrease of prior austenitic grain size.

(2) The difference of fatigue strength between various materials mainly depends on the difference of cycles required to initiate crack and behaviour of the very early crack growth.

(3) The stage of intermediate crack growth is hardly influenced by metallurgical factors of steels.

(4) The ratio of cyclic yield strength to monotonic one for steels peak-aged is lower than that for steels otherwise treated.

I. Introduction

Though many papers have been reported on the behaviour of fatigue crack growth of high strength steels, most of them are concerned to the intermediate crack growth rate. The rate of crack growth, da/dN , is generally expressed as a function of stress intensity factor, ΔK .

There are some examples that the value of da/dN is influenced by the metallurgical factors: (1) The use of high austenizing temperature to obtain a high fracture toughness causes a high value of da/dN due to the overheating in the 4340 steel.¹⁾ (2) The value of da/dN increases due to intergranular fracture in the secondary hardened 0.27C-5Mo steel.²⁾ (3) A two phased-mixed structure is not effective in reducing the da/dN in the In-744 steel because a preferential crack growth occurs through a weaker phase.³⁾ (4) The value of da/dN is influenced by the tempering temperature in the range between 200°C and 650°C in the S45C steel.⁴⁾ (5) The value of da/dN at a given ΔK in the austenitic steels is generally larger than that in the martensitic steels.⁵⁾

On the other hand, there are examples which contradict against the above: (1) The mechanical and metallurgical properties of various high yield strength martensitic steels are shown to have negligible effects on the value of da/dN in air.⁶⁾ (2) The change of the size of precipitates or the change of the density of dislocations by heat treatments hardly affects the da/dN value in the Ni-Al-Cu-C steel.⁷⁾

As the results of the analysis of the above papers, it is concluded that the value of da/dN at the intermediate range of the fatigue crack growth rate is not influenced by the metallurgical factor in the high tensile strength steels if the structures of crystals are same except the cases such that the intergranular fracture arises easily. Though the fatigue strength of smooth specimens is correlates with the yield strength or the ultimate tensile strength, the fatigue strength of specimens with sharp notch is not correlated with them. This fact suggests that the behaviour of the fatigue crack initiation is rather influenced by the metallurgical factor compared to that of the fatigue crack propagation. However, a few papers have been shown on the relationship between the fatigue crack initiation and the metallurgical factor because of the difficulty of how-to-deal with.

The purpose of the present work is to examine the relationship between the microstructures and the fatigue properties using the 5.5Ni-Cr-Mo-V (HY140) steel with various strength levels which were obtained by changing the condition of heat treatments.

II. Experimental Procedures

1. Materials

The 17 kg-ingots of the HY140 steel were made by vacuum-melting in a high frequency electric furnace, and were forged and rolled at 1200°C down to about 22 mm ϕ bars. The heat treatments which were used is shown as the chart at the bottom of this page.

* Originally published in *Tetsu-to-Hagané*, **63** (1977), 1700, in Japanese. English version received August 21, 1979.

** Tsukuba Laboratories, National Research Institute for Metals, Sengen, Sakura-mura, Niihari-gun, Ibaraki 305.

Table 1. Chemical composition. (wt%)

Steel	C	Si	Mn	Ni	Cr	Mo	Cu	V	P	S	Al	Co
HY 140	0.13	0.25	1.10	5.5	0.58	0.84	1.0	0.10	0.004	0.006	0.05	—
HY 180	0.11	0.12	0.15	10.0	2.0	1.0	—	—	<0.01	<0.007	—	8
MAG*	0.03	0.08	0.08	11.9	4.56	2.89	—	—	0.004	0.006	0.25	—

* MAG : 12% maraging steel

Table 2. Prior austenitic grain size and structures.

Steel	Mark	Prior-austenitic grain size (μm)	Structures
5.5Ni-Cr-Mo-V (HY140)	F 30	<10	Martensite+40% Bainite
	F 44	<10	Martensite
	N 30	20~30	Martensite+40% Bainite
	M36	”	Martensite+10% Bainite
	M44	”	Martensite
	MSH	”	Tempered Martensite
	MAC	”	Martensite
	MAS	”	”
10Ni-8Co-Cr-Mo (HY180)	L 30	200~300	Martensite+40% Bainite
	HY180	20~30	Tempered Martensite
12Ni maraging	MAG	<10	”

The fine microstructure was obtained by the cyclic quenching into water of five times at 850°C, and the coarse microstructure was obtained by the quenching after holding 2 hr at 1 250°C. The Ms point was about 330° to 340°C regardless of prior austenitic grain size. The retained austenite was not detected by the X-ray analysis. The microstructures were analysed using optical micrographs, transmission electron micrographs, and thermo-expansion curves for transformations.

The structure of all materials consists of high density of dislocations with laths. The materials except the MSH, M44, F44, and M36 materials contained the acicular precipitates of 0.2 to 0.8 μm length or the lamellar-like-precipitates, or the both. The MSH material contained the mass-like-precipitates of 0.2 to 0.3 μm and lath boundary precipitates except the above precipitates. No existence of precipitates was confirmed in the F44 and M44 materials.

The 10Ni-8Co-Cr-Mo (HY180) steel, which was tempered at 510°C, and the 12Ni maraging steel, which was aged at 480°C for 4 hr, were also used. The lath martensitic structures were observed in them.

The chemical composition is shown in Table 1, and the prior austenitic grain sizes and microstructures are shown in Table 2.

2. Fatigue Test

A±5 t electro-servo-hydraulic fatigue testing machine was used under tension to compression at the load ratio, $R(=K_{min}/K_{max})$, of -1, where K_{max} and

K_{min} are the maximum stress intensity factor and the minimum stress intensity factor respectively. The tests were performed in air at the frequency of 10 to 45 cycle/min. The cyclic yield strength, $\sigma_{y,c}$, and the cyclic work hardening coefficient, n' , were obtained from the cyclic stress-strain curves by the incremental step method.⁸⁾ The crack length was measured by a travelling microscope directly without taking off specimens from grips.

3. Fatigue Specimen

The 4 mm thick and 10 mm wide plate specimens with single side notch were used.

- 1) For the measurement of cycles to failure; specimens with the notch of 3.4 mm notch radius were used.
- 2) For the measurement of crack length; specimens with the notch of 0.2 mm notch radius were used.

4. Tensile Test Specimen

Round bars with the diameter of 4 mm and with the gauge length of 20 mm were used.

III. Results

1. Tensile Test

Examples of monotonic stress-strain curves are shown in Fig. 1. Ultimate tensile strength, σ_B , total elongation, ϵ_t , uniform elongation, ϵ_u , reduction in area, ϕ , and monotonic work hardening coefficient, n , are shown in Table 3. The following facts are obtained from the Tables 2 and 3.

(1) The values of σ_B and $\sigma_{y,m}$ increase with decrease of the prior austenitic grain size (see L30, M30, and F30).

(2) The value of $\sigma_{y,m}$ of the M44 is about 15 kg/mm² higher than those of the MAC or the MAS materials though no differences in the prior austenitic grain size and the dislocation density exist between them.

(3) The value of n of the MSH and the HY180 materials which were aged to almost peak hardness are about 0.03 to 0.04, and the value is the lowest in all the materials used. On the other hand, the n -values of the MAC material cooled in air and of the MAS material as rolled are about 0.09, and the value is the highest in the present materials. The n -value generally increases with the decrease of the holding temperature after quenching. No relationship between n and prior austenitic grain size is confirmed.

(4) A linear relation exists locally between n and $\sigma_{y,m}/\sigma_B$ as shown in Fig. 2.

2. Fatigue Test

1. S-N Curves

Cycles to failure, N_f , crack initiation cycles (cycles required for cracks to propagate from the tip of a notch to the length of 150 μm), N_i , and crack propagation cycles, $N_p (= N_f - N_i)$, are expressed as a function of stress amplitude, $\Delta\sigma/2$, in Figs. 3 (a) to (c). Strictly speaking, latent cycles consumed before crack initiation are involved in the crack initiation cycles. The following can be made clear in Fig. 3.

(1) No difference is observed between the trend of the $\Delta\sigma/2$ vs. N_f curves and that of the $\Delta\sigma/2$ vs. N_i curves. The curves are different depending on the condition of the heat treatment in the HY140 steel. But the relation between $\Delta\sigma/2$ and N_p are expressed as a curve, which is not influenced by the condition of the heat treatments or steels. This means that the process of the fatigue crack propagation is hardly affected by the amount or the size of precipitates, the size of the prior austenitic grain, tensile strength, etc.

(2) The fatigue strength, $\Delta\sigma_w/2$, for 10^5 cycles is the highest in the F44 materials heat-treated to obtain fine grains and the HY180 steel. The value

Fig. 1. Examples of stress (σ)–strain (ε) curves.

of that is about 56 kg/mm^2 . The lowest fatigue strength is 38 kg/mm^2 in the L30 material with the coarse grains. The materials with intermediate grains have different values of $\Delta\sigma_w/2$, depending on the condition of the heat treatment.

It is concluded that the metallurgical factors influence the fatigue crack initiation and the early stage of crack propagation, but hardly influence the intermediate stage of crack propagation. The reason why the fatigue strength for 10^5 cycles was used as a fatigue strength is that the use of the higher frequency was beyond the capacity in our testing machine.

2. Fatigue Crack Growth Rate

The relationships between da/dN and K_{max} are shown in Fig. 4. The slopes, m , defined by $da/dN \propto K_{\text{max}}^m$ are 2 to 3. The da/dN is almost expressed only as a function of $K_{\text{max}} (= \Delta K/2)$, regardless of structures and, or chemical compositions in the present materials. This fact is consistent with the content of Fig. 3 (c).

3. Cyclic S-S Curves

All materials used in the present work were cyclic softened. Particularly, the MSH and HY180 ma-

Fig. 2. The relationship between ratio of monotonic yield strength ($\sigma_{y,m}$) to ultimate tensile strength (σ_B) and monotonic work hardening coefficient (n).

Table 3. Mechanical properties.

	σ_B (kg/mm^2)	$\sigma_{y,m}$ (kg/mm^2)	ε_t (%)	ε_u (%)	ϕ (%)	$\sigma_{y,c}$ (kg/mm^2)	n	n'	$\sigma_{y,m}/\sigma_B$	$\sigma_{y,c}/\sigma_{y,m}$
F 30	136.2	108.3	14.4	7.0	67.3	97.8	0.077	0.18	0.80	0.90
F 44	140.2	117.9	14.3	5.9	68.5	113.1	0.062	0.18	0.84	0.96
M30	130.8	104.3	17.6	8.4	66.8	92.4	0.073	0.18	0.80	0.89
M36	131.5	111.3	12.9	4.7	67.6	105.5	0.058	0.18	0.85	0.95
M44	136.3	114.3	14.5	6.1	66.8	111.7	0.058	0.16	0.84	0.97
MSH	116.5	112.1	17.3	8.5	70.8	92.0	0.038	0.19	0.96	0.82
MAC	134.0	101.9	14.9	7.6	67.7	93.0	0.089	0.22	0.76	0.91
MAS	129.3	96.9	15.7	8.0	68.9	86.5	0.093	0.20	0.75	0.89
L 30	125.2	102.4	14.9	7.7	58.0	90.5	0.069	0.12	0.82	0.88
HY180	139.7	129.0	13.8	5.1	72.6	112.7	0.032	0.15	0.92	0.87
MAG	117.7	112.8	14.0	1.5	68.6	97.8		0.12	0.96	0.87

σ_B : Ultimate tensile strength
 $\sigma_{y,m}$: 0.2% yield strength (monotonic)
 ε_t : Total elongation
 ε_u : Uniform elongation

ϕ : Reduction of area
 $\sigma_{y,c}$: 0.2% yield strength (cyclic)
 n : Work hardening coefficient (monotonic)
 n' : Work hardening coefficient (cyclic)

(a) Stress amplitude ($\Delta\sigma/2$) vs. cycles to failure (N_f).
(b) Stress amplitude ($\Delta\sigma/2$) vs. crack initiation cycles (N_i).
(c) Stress amplitude ($\Delta\sigma/2$) vs. crack propagation cycles (N_p).

Fig. 3. Stress amplitude vs. cycles.

materials which were aged to peak hardness are cyclic softened in all the range of the strain as shown in Fig. 5 (a). The same trend is observed in the MAG material. The values of $\sigma_{y,c}$, n' , and $\sigma_{y,c}/\sigma_{y,m}$ are shown in Table 3. The value of $\sigma_{y,c}/\sigma_{y,m}$, which means the degree of softening at lower range of $\Delta\epsilon$, is 0.82 to 0.87.

On the other hand, the degree of softening of the materials with the martensitic structure or the mixed structure of martensite and bainite is quite small at the lower range of $\Delta\epsilon$, as shown in Fig. 5 (b). With $\Delta\epsilon$ increasing, the degree of softening increases.

The value of $\sigma_{y,c}/\sigma_{y,m}$ of the F44 and M44 materials with the quenched martensitic structure is 0.96 to 0.97. The value of $\sigma_{y,c}/\sigma_{y,m}$ of the materials

Fig. 4. Crack growth rate (da/dN) vs. maximum stress intensity factor (K_{max}).

Fig. 5. Monotonic and cyclic stress (σ)-strain (ϵ) curves.

with the mixed structure or the materials air-cooled is 0.88 to 0.95.

IV. Discussion

1. Fatigue Strength and Microstructure

Persistent slip bands are locally formed on the specimen surface under a cyclic load prior to the crack initiation. The size of the fracture unit is almost equivalent to the crystal grain with the high angle boundary like a lath-packet or block boundaries at the threshold region in high strength steels.⁹⁾ Therefore, it is reasonable to consider that the crystal grain like lath-packet or block with the minimum size in various kinds of crystal grains with a high angle boundary is a grain concerned to the crack initiation at around the endurance limit stress level. And the endurance limit is associated with a crack-crossing over a high angle boundary adjacent to the

grain in which a plastic deformation was saturated. On the base of the analogy of the fracture mechanics,^{10,11)} the size of the plastic deformation, γ_d , at the tip of the dull notch just like in the present specimen is expressed as follows: $\gamma_d \propto (\Delta K / \sigma_{y,c})^2$. The smaller the γ_d , the higher the number of cycles to propagate a given distance. It is expected that when the values of $\sigma_{y,c}$ and $\Delta\sigma$ are kept constants, the value of γ_d increases with the increase of the size of the crystal grain with a high angle boundary. Therefore, with the grain size increasing, da/dN becomes higher.

According to the above, the difference of N_f at the lower $\Delta\sigma$ between steels shown in Fig. 3 relies on cycles to start a crack and cycles to propagate at the early crack growth region, which are influenced by the value of $\sigma_{y,c}$ and the size of the grain with a high angle boundary.

The prior austenitic grains in the present HY140 steel consist of lath-packets and blocks, as shown in Photo. 1. It is reported that their size increases as the size of prior austenitic grains increases.¹²⁾

As it is difficult to measure the size of lath-packets or blocks, the size of the prior austenitic grain is used as the substitute of the size of the lath-packets or blocks in order to compare the size effect on the fatigue strength at 10^5 cycles, $\Delta\sigma_w/2$. The relationships between $\Delta\sigma_w/2$ and $\sigma_{y,c}$ are shown in Fig. 6, in which the effect of the prior austenitic grain size on the relation between $\Delta\sigma_w/2$ and $\sigma_{y,c}$ is also shown. The facts that when the prior austenitic grain size is kept constant, the value of $\Delta\sigma_w/2$ is proportional to the value of $\sigma_{y,c}$ and when the value of $\sigma_{y,c}$ is kept constant, the value of $\Delta\sigma_w/2$ is higher at the smaller prior austenitic grain size, suggest the propriety of the above way of thinking.

As the size of the prior austenitic grain of the HY180 steel was 20 to 30 μm , the $\Delta\sigma_w/2$ value of the steel should fit the "Intermediate" line in Fig. 6. However, the value is rather closer to the "Fine" line. This is because the microstructure in the prior austenitic grain of the HY180 steel is finer than that of the HY140 steel, as shown in Photo. 2 in spite of no difference in the size of the prior austenitic grain size between both the steels.

Photo. 1. Transmission electron micrographs of martensite of the F44 material. ($\times 20\,000$)

2. Cyclic Softening and Microstructure

The fatigue strength increased with increase of the value of $\sigma_{y,c}$, as mentioned above. Therefore, if one uses mechanical properties other than $\sigma_{y,c}$ as a standard in selecting a structural material in high strength steels, one tends to over-estimate the fatigue strength because these steels are easily cyclic softened. The heat treatment dependency of the cyclic softening is now discussed.

The followings are expected as factors, which influence the cyclic softening.^{7,13)}

- 1) Rearrangement of the dislocations, reduction in their density and the subsequent development of cell structures
- 2) Disordering of the precipitate structure
- 3) The generation of new mobile dislocations
- 4) Mechanical unpinning of dislocations

All materials used in the present experiment were cyclic softened. The substructure of all materials consists of dislocations of high density, which were introduced by the martensitic or bainitic transformation. The difference of the degree of the cyclic softening, $\sigma_{y,c}/\sigma_{y,m}$, between the materials depends mainly on the factors a) and b) as mentioned later. The value of $\sigma_{y,c}/\sigma_{y,m}$ of the present materials is classified into four groups by $\sigma_{y,m}/\sigma_B$ as shown in Fig. 7.

Group A (MSH, HY180, and MAG materials): The value of $\sigma_{y,m}/\sigma_B$ of the group A is 0.92 to 0.96, and is the highest among all the groups. On the other hand, the value of $\sigma_{y,c}/\sigma_{y,m}$ is 0.82 to 0.87, and is the lowest. All materials in the group A are the ones aged to obtain the peak hardness. The values of n in the MSH and HY180 steels are rather smaller compared to those of other materials, and the value of n in the MAG material must be smaller as the uniform elongation is extremely small as shown in Table 3. The values of n are characteristic of the materials strengthened by coherent particles, which are easily cut by dislocations.¹⁴⁾ The softening due

Fig. 6. Relationship between fatigue strength at 10^5 cycles ($\Delta\sigma_w/2$), cyclic yield strength ($\sigma_{y,c}$) and prior austenitic grain size.

Photo. 2. Examples of microstructures of various specimens. Etched by 3% nital.

Fig. 7. Difference of relation between yield strength ratio ($\sigma_{y,m}/\sigma_B$) and ratio of cyclic to monotonic yield strength ($\sigma_{y,c}/\sigma_{y,m}$) for various materials.

to the rearrangement of the dislocations in the materials strengthened by coherent particles hardly occurs under cyclic loading, but the softening results from the cutting of precipitates by dislocations even at low strain.^{7,13)}

Group B (F30, M30, and L30 materials) and Group C (MAG and MAS materials); The microstructures of the materials in the group B consist of the mixed structures of martensite and bainite, and those in the group C consist of the martensite, in which the acicular precipitates are dispersed. Relatively high values of n , as shown in Table 3, mean the lack of the coherency. The softening under cyclic loading results from the rearrangement of dislocations as shown in Photo. 3. The difference of the value of $\sigma_{y,m}/\sigma_B$ between the two groups should be due to the difference of the contents of precipitates.

Group D (M44, F44 and M36 materials); The microstructures of the group generally consist of the quenched-martensite except the M36 material which involves 10% bainite, and no precipitates were ob-

(a) Before fatigue test
(b) Just before fatigue failure at the strain range of $\pm 2\%$

Photo. 3. Transmission electron micrographs of the M30 material.

served in transmission electron micrographs. No cyclic softening is characteristic of the materials in the group D. It is not clear why the materials with the high density of dislocations which hardly contain precipitates are difficult to be cyclic softened.

It is noteworthy that the materials with the high values of $\sigma_{y,m}/\sigma_B$, which were aged or tempered to a peak hardness, were easily cyclic softened even at a low $\Delta\varepsilon$. As the high strength steels are generally used after aging or tempering to obtain the hardness close to a peak hardness, it is likely that one overestimates in terms of fatigue strength if one uses the value of $\sigma_{y,m}$ as a standard to select.

V. Conclusions

(1) The fatigue life at 10^5 cycles increases with increase of the cyclic yield strength and with decrease of the prior austenitic grain size.

(2) The difference of the fatigue life between the materials used mainly depends on the difference of cycles required to initiate crack and of cycles to propagate at the very early stage.

(3) The crack growth rate, da/dN , is expressed by the following equation at the intermediate stage of crack growth;

$$da/dN = BK_{\max}^m$$

where B is a constant and $m=2$ to 3. At the stage, the behaviour of the crack growth is hardly influenced by the metallurgical factors of steels.

(4) The ratio of cyclic yield strength to monotonic one for the steels aged or tempered to the peak hardness is much lower than that for steels other-

wise treated at a low strain range.

(5) The steels with high density of dislocations and no precipitates are hardly cyclic softened at a low strain range.

REFERENCES

- 1) R. O. Richie and J. F. Knott: *Met. Trans.*, **5** (1974), 782.
- 2) R. M. Hom: *Met. Trans.*, **6A** (1975), 1525.
- 3) H. W. Hayden and S. Floreen: *Met. Trans.*, **4** (1973), 561.
- 4) T. Araki, S. Seki and R. Sagawa: *Tetsu-to-Hagané*, **57** (1971), 2042.
- 5) A. G. Pineau and R. M. Pelloux: *Met. Trans.*, **5** (1974), 1104.
- 6) J. M. Barsom: *WRC Bull.* **194** (1974), 8.
- 7) R. A. Fournelle, E. A. Grey and M. F. Fine: *Met. Trans.*, **7A** (1976), 669.
- 8) R. W. Landgraf, J. Morrow and T. Endo: *J. Metals*, **21** (1969), 176.
- 9) M. Sumita, N. Maruyama and I. Uchiyama: *Tetsu-to-Hagané*, **65** (1979), 637.
- 10) F. A. McClintock: *ASTM Special Publ.*, **415** (1967), 70.
- 11) G. T. Hahn, R. G. Hoagland and A. R. Rosenfield: *Met. Trans.*, **3** (1972), 1189.
- 12) A. Kamata, N. Koshizuka and T. Funagoshi: *Tetsu-to-Hagané*, **60** (1974), 372.
- 13) C. Calabrese and C. Laird: *Mat. Sci. Eng.*, **13** (1974), 1418.
- 14) A. Kelly and R. B. Nicholson: *Progs. Mater. Sci.*, **10** (1963), 149.