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Effect of humidity on initiation and propagation properties of a fatigue crack of maraging steel

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Abstract Effect of humidity on fatigue properties of 18% Ni maraging steels was investigated using the steels with different hardness and aging structure under rotating bending by varying the relative humidity (RH) from 25% to 95%. Both of a crack initiation and its propagation in the early stage of fatigue process were accelerated by high humidity, causing the large decrease in fatigue strength. The fatigue strength at 10^7 cycles in RH85% decreased to less than 50% of the one in RH25%. By successive observation of the specimen surface at fatigue process and fracotgraphic analysis, it was concluded that the promotion of crack initiation was due to anodic dissolution and the acceleration of crack propagation was caused by the propagation of a brittle crack which was assisted by hydrogen atom generated in accompany of cathode reaction. The acceleration of crack propagation was suppressed by formation of reverted austenite.

Keywords Fatigue, Maraging steel, Humidity, Crack initiation, Crack propagation

1. Introduction

Maraging steel is an ultra high strength steel which is strengthened by means of many strengthening mechanisms such as precipitation strengthening, solution hardening, grain refinement strengthening and so on [1]. However, the fatigue strength is very lower than expected from its static strength similar to other high strength steels. One of the reasons for low resistance to fatigue is due to its high susceptibility for humidity [2]. Moreover, the effect of humidity on fatigue strength largely depends on hardness, microstructure and so on. While, studies on effect of humidity on fatigue properties of maraging steel were very limited in comparison with those on the resistance to stress corrosion cracking of the steel [3].

In the present study, in order to investigate the effect of humidity on crack initiation and its propagation behavior of 18%Ni maraging steels with different hardness and aging structure, fatigue tests were carried out in various relative humidity under rotating bending.

2. Experimental procedures

The materials used were a 300-grade and a 350-grade of 18% Ni maraging steels. The chemical compositions in mass % of the steels were shown in Table 1.
The steels were solution treated for 5.4ks at 1123K in vacuum, followed by air cooling and age hardened at different conditions in a salt bath. Mean grain sizes of a prior austenite were about 20 μm in both steels.

Figure 1 shows aging curves. Aging conditions examined were under-aging and over-one which showed nearly the same hardness of 550HV in 300-grade steel and peak-aging of HV705 in350-grade as indicated by circles in Fig. 1. These aging conditions were selected to investigate the effects of hardness and reverted austenite on fatigue properties in high humidity. That is, it was confirmed that the over-aged steel contained 10% of reverted austenite but no reverted austenite

Table 1. Chemical composition (mass %)

Grade	C	Si	Mn	Ni	Mo	Co	Ti	Al	Fe
300G	0.005	0.05	0.01	18.47	5.14	9.09	0.89	0.11	Bal.
350G	0.001	0.01	0.01	17.89	4.27	12.36	1.3	0.08	Bal.

was in other steels by using X ray diffraction. In the following, these steels will be denoted as Steel A, Steel B and Steel C, respectively as shown in Fig. 1 and Table 2.

Table 2 shows mechanical properties of the steels.

Figure 2 shows shape and dimensions of specimens. Fatigue strength was investigated by using plain specimens, and successive observation of specimen surface was carried out by using partially notched specimens which was localized the crack initiation site. Specimens were machined after solution treatment, and then aged at the conditions shown in Fig. 1. Prior to fatigue testing, all of the specimens were paper and electro polished to remove the work affected layer and make the observation easier. Fatigue tests were carried out using a rotating bending fatigue testing machine with a capacity of 15 N·m operating at about 50Hz in relative humidity (RH) of 25%, 45%, 65%, 85% and 95%. The accuracy of humidity was RH±5%. The temperature in atmosphere was not

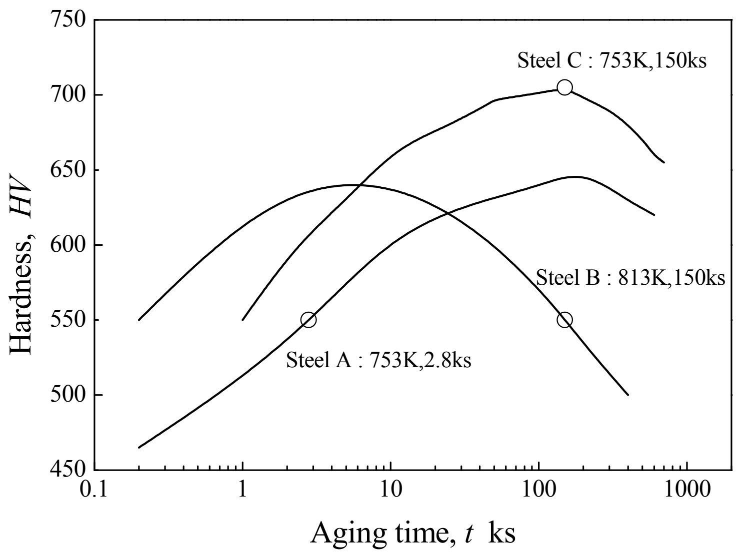
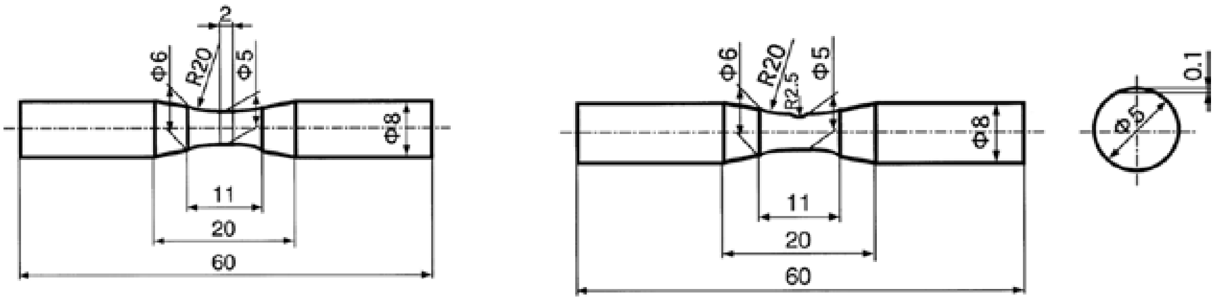


Figure 1. Aging curves

Table 2. Mechanical properties

Steel	Aging condition	Vickers hardness *HV*	0.2% proof stress $\sigma_{0.2}$ (MPa)	Tensile strength σ_B (MPa)	Reverted austenite γ (%)
A	753K,2.8ks	550	1730	1833	0
B	813K,150ks	550	1634	1798	10
C	753K,150ks	705	2300	2370	0



(a) Plain specimen (b) Partially notched specimen

Figure 2. Shape and dimensions of specimens

controlled, but the temperature range was 298±3K. Observation and measurement of the changes in the surface state of a specimen and crack length due to stress repetitions were carried out by plastic replication technique. Crack length *a* was defined as the surface length along to the circumferential direction on the specimen surface. Fracture surfaces were observed by using scanning electron microscope (SEM).

3. Result and discussion

3.1 Effect of humidity on fatigue properties

Figure 3 shows *S-N* curves of Steel A and Steel C in various environments showing the effect of hardness on humidity dependence of fatigue strength. All of the fracture occurred from the specimen surface in both humidity. Moreover, in low humidity, any surface cracks were not observed in non-fractured specimen at the fatigue limit σ_w defined as fatigue strength at 10^7 cycles, meaning that fatigue limit was mainly controlled by the resistance to a crack initiation.

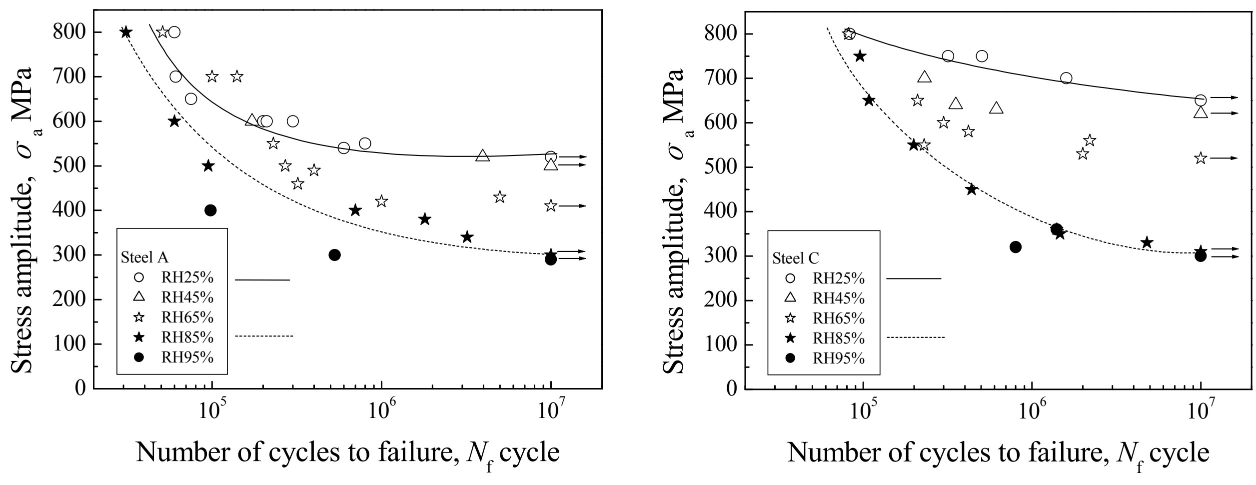


Figure 3. *S-N* curves of Steel A and Steel C in various humidity

Figure 4 shows humidity dependence on fatigue limit. Effect of humidity on fatigue strength was very small below about humidity of RH50%, and over the humidity, fatigue strength was largely decreased with increasing in humidity. The decrease in fatigue strength was larger in high strength steel. For example, fatigue limit of Steel C in RH85% was decreased to below a half of the one in RH25%. Such humidity conditions are not special cases in daily service of machines and structures. Therefore, the marked decrease in fatigue strength is very important result to be considered in practical application.

Figure 5 shows crack growth curves and the crack length against to relative number of cycles to failure N/N_f in RH25% and RH85%. Figure 6 shows relation between crack growth rate and stress intensity factor range. As seen from these figures, the initiation of a crack and its early propagation are accelerated by high humidity and most of fatigue life is occupied by the growth life of a crack in high humidity. On the other hand, the growth rate of crack longer than about a few of grain sizes of a prior austenite are not influenced by humidity in both steels. In addition, the difference in the

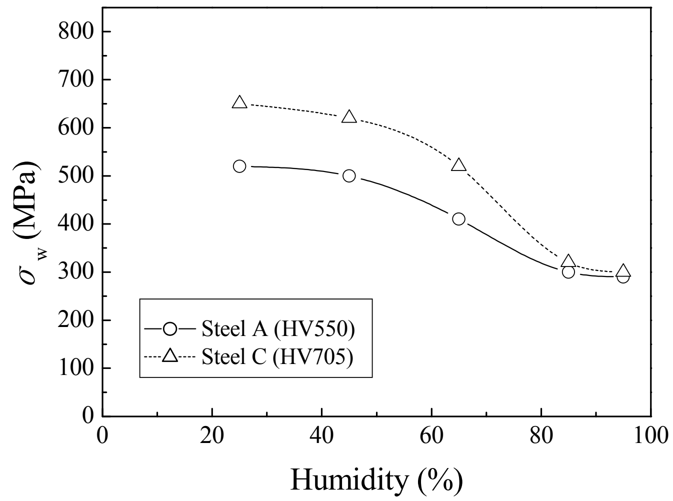
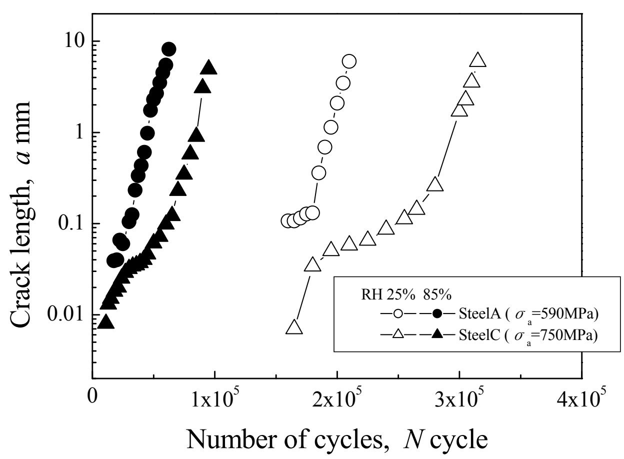
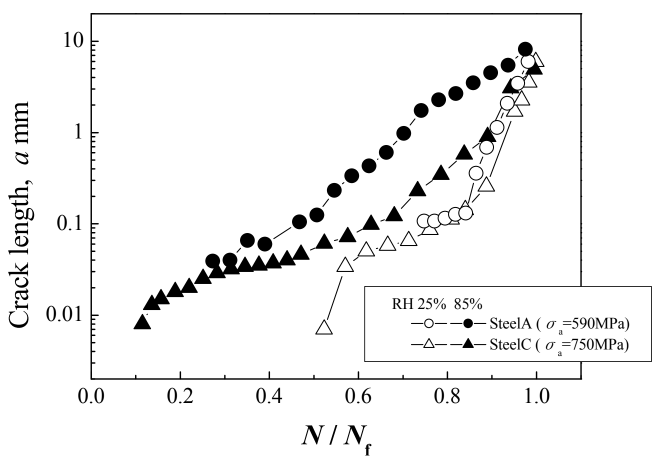


Figure 4. Humidity dependence of fatigue limit in Steel A and Steel C



(a) a-N curves



(b) a-N/N_f curves

Figure 5. Crack growth curves of Steel A and Steel C

crack propagation rate by hardness is very small. These results indicate that the decrease in fatigue strength was mainly caused by the accelerations of the initiation of a crack and the crack propagation in the early stage of fatigue process in both steels.

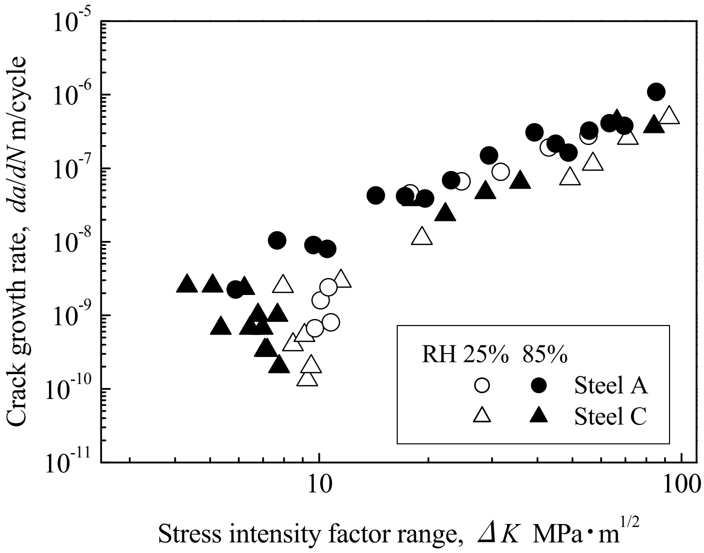
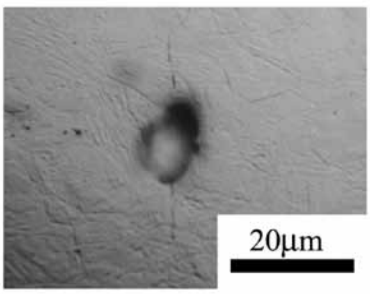
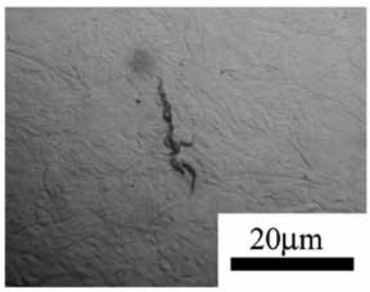


Figure 6. Crack growth rate against to stress intensity factor range in Steel A and Steel C

Figure 7 shows examples of cracks in the early propagation process of specimen of Steel C in RH25% and RH85%. A pit at crack initiation site in RH25% was generated by electro-polishing before fatigue test. A crack in RH85% is relatively wide in comparison with the one in RH25%, suggesting that a crack initiation was promoted by humidity through anodic dissolution. This may be a main reason for the promotion of a crack initiation by high humidity.



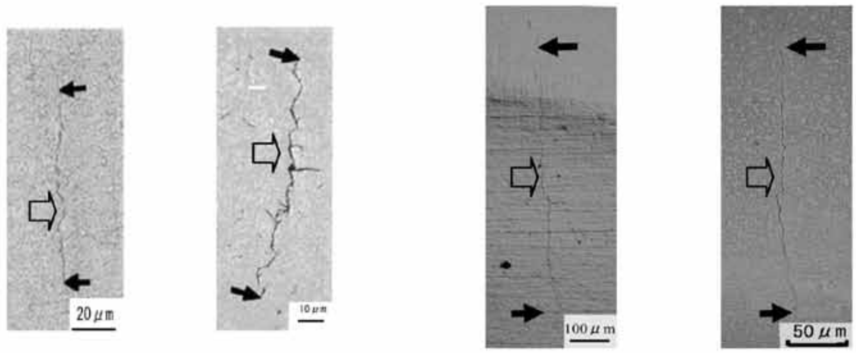
(a) RH25%



(b) RH85%

Figure 7. Feature of crack of Steel C (⟵⟶ Axial direction)

Figure 8 shows crack morphologies of Steel A and Steel C in both humidity. In Steel A, a crack propagates in zigzag manner along grain boundaries in high humidity, though it is a straight crack in low humidity. That is, the growth in high humidity was caused by an intergranular crack and that in low humidity was a transgranular crack. On the other hand, in case of Steel C, it is not confirmed the influence of humidity on crack morphologies in so far as the surface observation. However, even in Steel C as seen from Fig. 9, brittle facets are also observed near the crack initiation site in RH85% as shown by mark ⇒, though they are not in RH25%. Therefore, the acceleration of crack propagation was caused by hydrogen embrittlement in both steels.

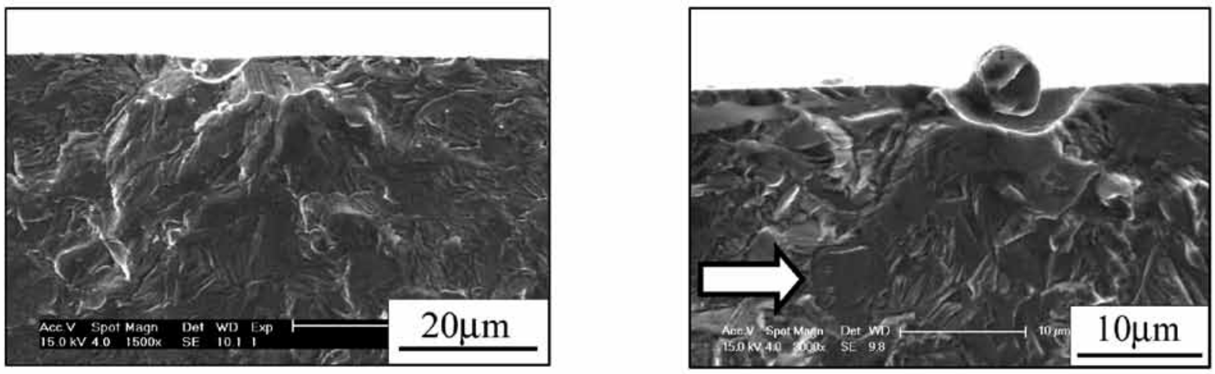


(a-1) RH25% (a-2) RH85% (b-1) RH25% (b-2) RH85%

(a) Steel A (b) Steel C

(⇨ : Crack initiation site, ➡ : Crack tip)

Figure 8. Crack morphologies of Steel A and Steel C (←→ axial direction)



(a) RH25% (b) RH85%

Figure 9. Fracture surface of Steel C

3.2 Effect of reverted austenite on fatigue properties in high humidity

Figure 10 shows *S-N* curves of Steel B with reverted austenite in RH25%, RH65% and RH85%. In the figure, results of Steel A which contains no reverted austenite shown in Figure 3 are also indicated by lines only. The effect of humidity is very small in the Steel B in comparison with Steel A, though these steels have the same hardness.

Figures 11 and 12 show crack growth curves and relation between crack growth rate and stress intensity factor range of Steel B in humidity of RH25% and RH85%. In Fig. 12, the results of Steel A are also indicated. As seen from these figures, the acceleration of the propagation of a small crack is hardly observed in Steel B, though the crack initiation is promoted by high humidity.

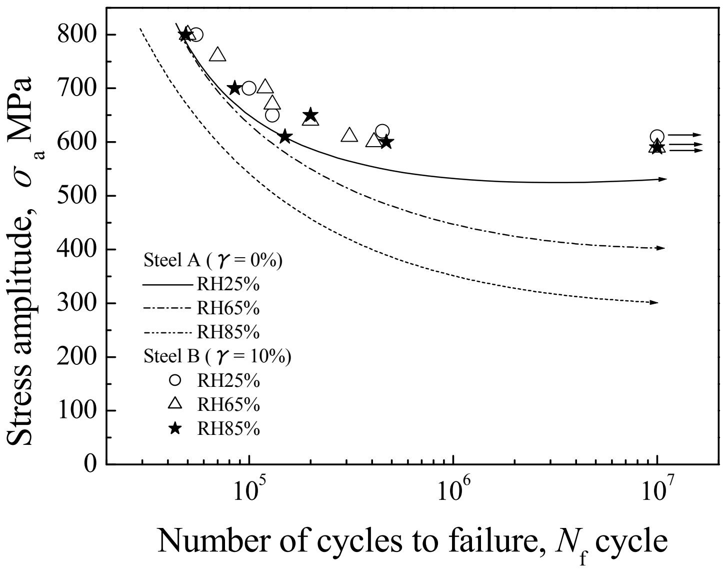


Figure 10. *S-N* curves of Steel B

Moreover, not only the effect of humidity but also the one of aging structure on the crack growth rates are not observed.

Figure 13 shows crack morphology of the Steel B in humidity of RH25% and RH85%. There is no or little difference in the morphologies in both humidity and also in comparison with Steel A in 25% similar to crack growth rate mentioned above. This may be explained from that reverted austenite widely distributed in the matrix [4] becomes trap sites of hydrogen [5, 6] and suppresses the acceleration of crack propagation assisted by hydrogen yielded in Steel A stated above.

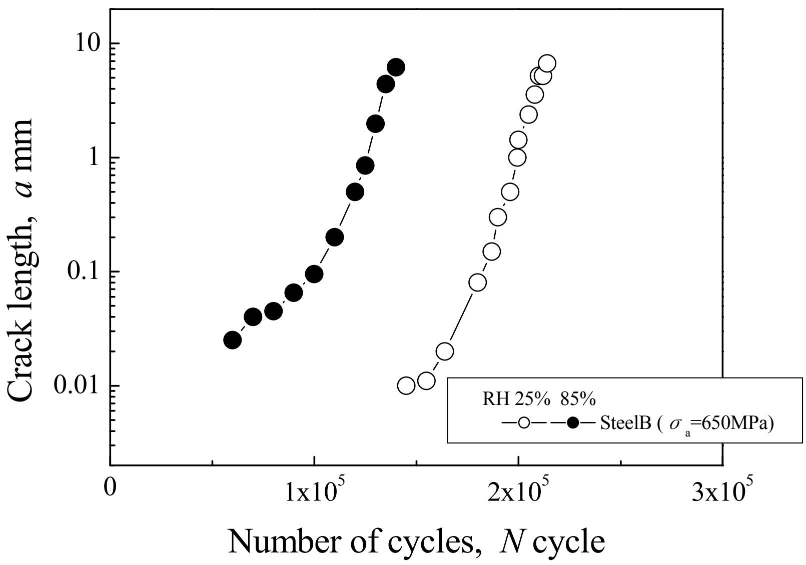


Figure 11. Crack growth curves of Steel B

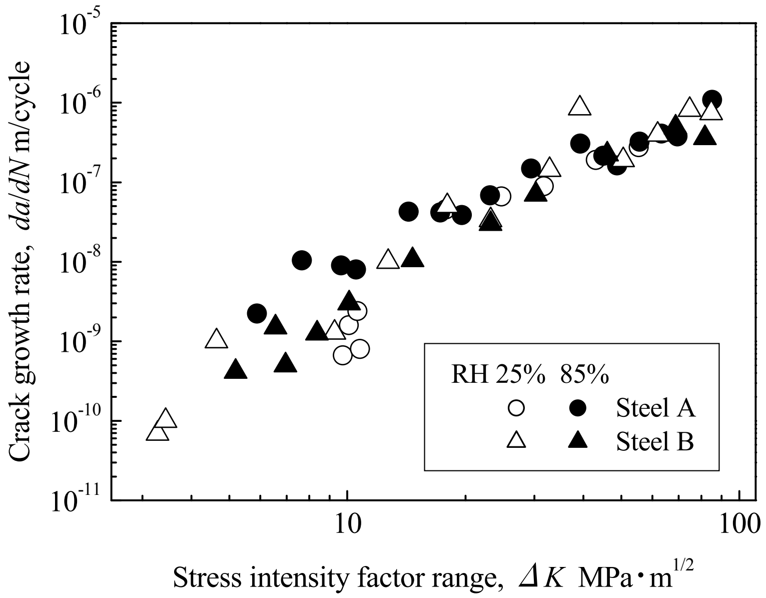
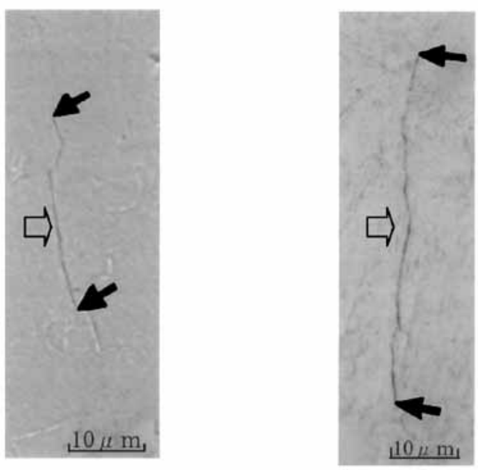


Figure 12. Crack growth rate against to stress intensity factor range in Steel B



(a) RH25% (b) RH85%

(⇨ :Crack initiation site, ➞ :Crack tip)

Figure 13. Crack morphology of Steel B (⟷ axial direction)

4. Conclusions

The effects of humidity and aging structure on initiation and propagation of a fatigue crack of maraging steels were investigated in various relative humidity (RH). Fatigue strength was largely decreased by high humidity, though the decrease in fatigue strength was very small below humidity of RH50%. The main reason for the decrease in fatigue strength was accelerations of both of a crack initiation and its propagation in the early stage of fatigue process. The propagation of a larger crack was not influenced by humidity. By successive observation of fatigue process and fracotgraphic analysis, the promotion of crack initiation was due to anodic dissolution and the acceleration of crack propagation was embrittlement due to hydrogen generated in cathode reaction. The acceleration of crack propagation was suppressed by formation of reverted austenite.

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