Initiation and Propagation Behavior of a Fatigue Crack of Maraging Steel in High Humidity

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Abstract The effect of humidity on the fatigue properties of 18% Ni maraging steels with different hardness and aging structure was investigated under rotating bending fatigue by varying relatively humidity from 25% to 95%. It was found that the initiation and the early propagation of a fatigue crack were accelerated in high humidity, which caused to a large decrease in fatigue strength of the alloys. In fact, the fatigue strength at 10^7 cycles obtained in RH 85% was less than a half of that in RH25%. Meanwhile, successive observation on surface fatigue progress and the fractographic analysis of fractured specimens elucidated that anodic dissolution was the main reason for promoting crack initiation whilst hydrogen embrittlement due to cathode reaction was responsible for the acceleration of crack propagation. However, the acceleration of crack propagation was suppressed by the formation of reverted austenite.

Keywords Fatigue, Maraging steel, Humidity, Ageing condition, Fatigue mechanism

1. Introduction

Maraging steel is a kind of ultrahigh strength steel that involves many strengthening mechanisms such as precipitation hardening, solid solution hardening, grain refinement and so on [1]. However, fatigue strength of maraging steel was much lower than expected on basis of its static strength, especially when compared to other steels of similar high static strength. One reason for the low resistance of the alloy to fatigue is due to its high susceptibility to humidity [2]. It is known that the effect of humidity on fatigue strength varies largely with hardness, microstructure and many other factors. However, information on the effect of humidity on the fatigue properties of maraging steel was very limited in comparison with those on its resistance to stress corrosion cracking [3].

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

2. Experimental procedures

The materials used were a 300-grade and 350-grade 18%Ni maraging steels. The chemical compositions in mass% of the alloys are shown in Table 1. The steels were solution treated for 5.4ks at 1123K in vacuum followed by air cooling and age hardening in a salt bath. The mean grain size of prior austenite was about 20μm in the both alloys. Table 2 shows mechanical properties of the alloys subjected to various age hardening treatments.

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.

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 (300G)	753K,2.8ks	550	1730	1833	0
B (300G)	813K,150ks	550	1634	1798	10
C (350G)	753K,150ks	705	2300	2370	0

Figure 1 shows the aging curves of maraging steels. Aging conditions were determined in such a way that the 300-grade steel was either under-aged or over-aged so that it had nearly the same hardness of 550HV but different structures, while the 350-grade steel was peak-aged and had a hardness of 705HV. The above mentioned ageing conditions are indicated by circles in Fig. 1, respectively. X-ray diffraction detected that only the structure of over-aged steel featured with 10% of reverted austenite. Therefore, the effects of the hardness and the reverted austenite can be examined separately. The under-aged, over-aged and peak-aged 18%Ni maraging steels will be denoted hereafter as Steel A, Steel B and Steel C, respectively.

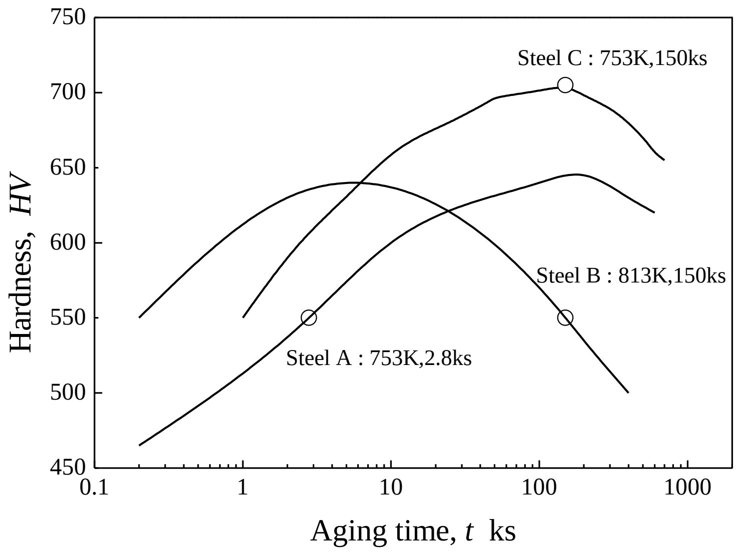


Figure 1. Aging curves of maraging steels

Figure 2 shows shape and dimensions of specimens. Fatigue strength was investigated by using plain specimens (Fig. 2a). To localize crack initiation and to better observe, partially notched specimens (Fig. 2a) were employed. Specimens were machined after solution treatment, and then aged at the different conditions displayed in Fig. 1. Prior to fatigue testing, specimens were electropolished to remove work affected layer and to better observe. Fatigue tests were carried out using a Ono-type rotating bending machine with a capacity of 15 N·m, operating at about 50Hz in the relative humidity (RH) of 25%, 45%, 65%, 85% and 95%, respectively. The humidity was controlled in the range of RH±5% while the temperature without control fell in the range of 298±3K. Surface observation and crack length measurement were conducted using plastic replication technique. Crack length, *a*, was defined along circumferential direction vertical to stress axis. Fracture morphology was analyzed under scanning electron microscope (SEM).

3. Results and discussion

3.1 Effect of humidity on fatigue properties

Figure 3 shows *S*-*N* curves of Steels A and C in different humidity, respectively. Fatigue strength decreases significantly with increasing humidity, irrespective of the kind of steels.

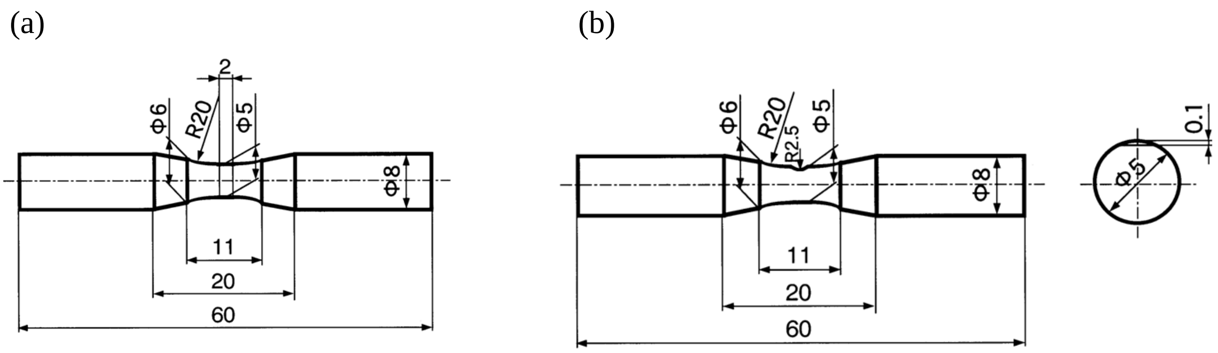


Figure 2. Shape and dimensions of (a) plain and (b) partially notched specimens

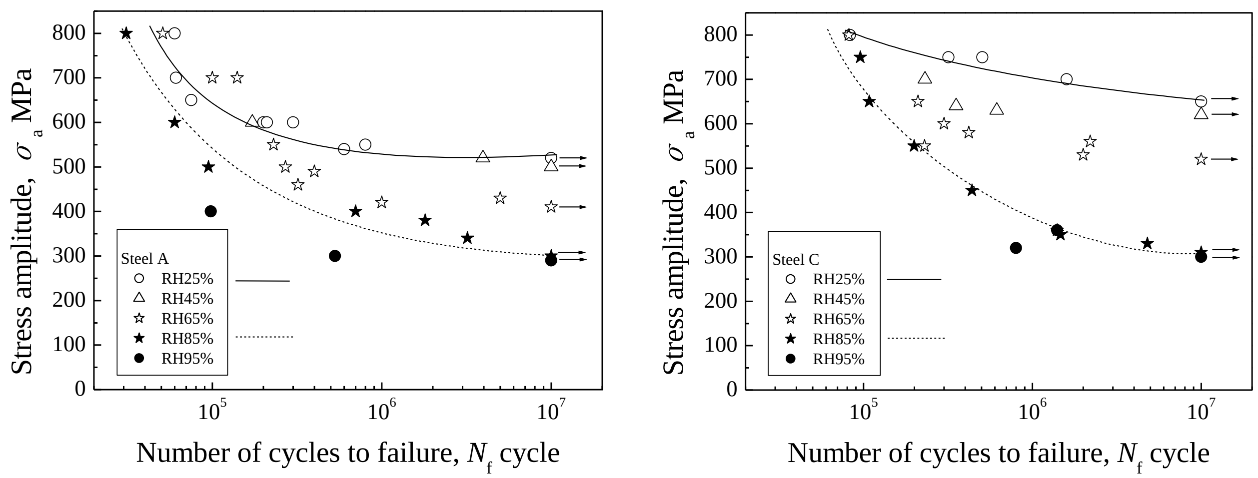


Figure 3. Variation of fatigue strength with humidity in Steels A (left) and C (right)

All of fractures originated from the surface. In low humidity, crack was not observed on the surface of non-fractured specimens tested at the stress level of fatigue limit, σ_w, which is defined as the strength for a specimen not to fail after being stressed for 10^7 cycles. In this case, it means that the fatigue limit of the alloys was determined by the resistance to crack initiation.
Figure 4 shows the humidity dependence of the fatigue limit. Effect of humidity on fatigue strength was relatively small in the range of low humidity below about RH50%. In the high humidity beyond RH50%, fatigue strength decreased largely with increasing humidity, especially the higher the static strength, the larger the decrease in fatigue strength. For example, the fatigue limit of Steel C in RH85% was less than a half of that in RH25%. The humidity examined in the current study was not particular but normal so that this marked decrease of fatigue strength in high humidity is of extremely importance in the practical applications of the alloys.
Figure 5 shows (a) crack growth curves and (b) the relation between crack length and the ratio of number of cycles to fatigue life, N/N_f, in low (RH25%) and high (RH85%) humidity, respectively.

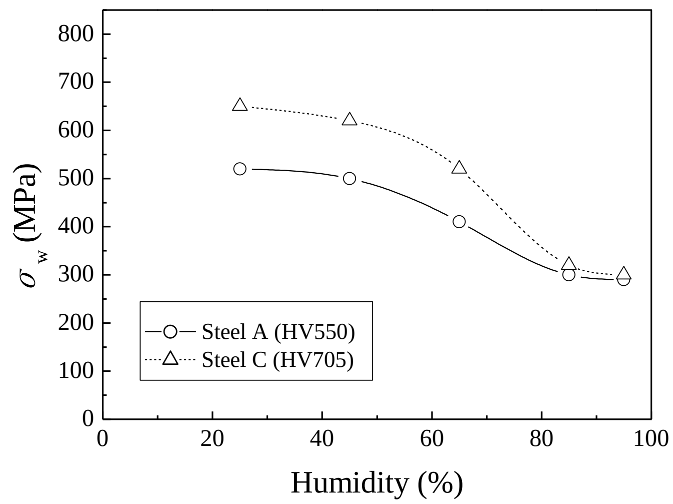
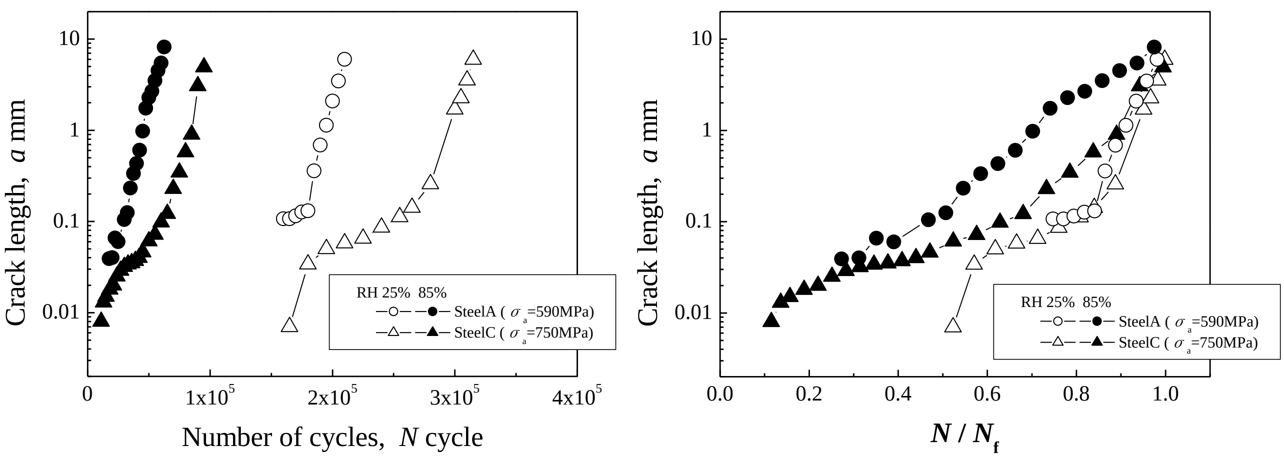


Figure 4. Humidity dependence of fatigue limit



(a) a-N curves (b) a-N/N_f curves

Figure 5. Crack growth behavior

Both the initiation (a few grain sizes) and its early propagation (~0.16 mm) are accelerated by high humidity. Most of fatigue life (70-90%) is spent in growing a crack up to ~1 mm. On the other hand, the influence of humidity on crack growth rate is not remarkable when cracks extend to ~8 grain sizes of prior austenite, and neither is the effect of hardness, as shown in Fig. 6, indicating that the accelerations to crack initiation and early crack propagation are the main reasons for the decrease of fatigue strength in high humidity.

Figure 7 shows the effect of humidity on the feature of typical small cracks observed in Steel C. The edges of a crack corroded in RH85% look relatively wide opened in comparison with those in RH25%, suggesting the promotion of crack initiation in high humidity through anodic dissolution.

The effect of humidity on crack morphology is shown in Fig. 8. In case of Steel A, a crack that propagated in a zigzag way along grain boundaries in high humidity grew almost vertically to stress axis in low humidity. In case of Steel C, however, the influence of humidity is hardly recognized by merely optical surface observation.

Figure 9 shows morphology of fracture surfaces in Steel C. It is found that even in Steel C, brittle facets are also observed in the vicinity of crack initiation site in high humidity, arrowed in Fig. 9b, though no brittle facet is found in low humidity (Fig. 9a), which means that hydrogen embrittlement caused the acceleration of crack propagation in high humidity.

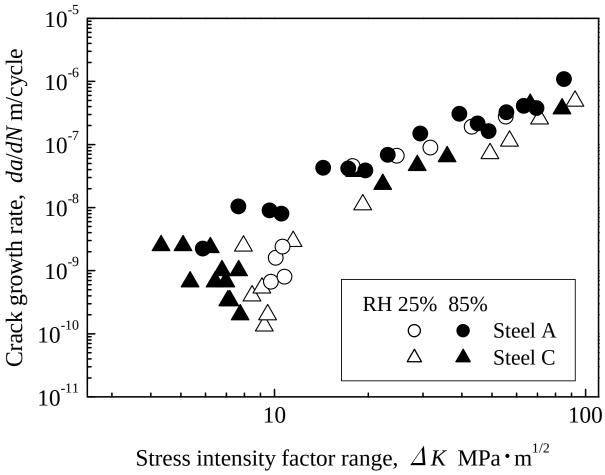
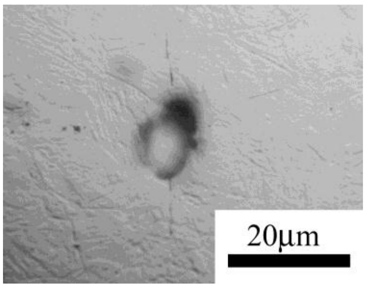


Figure 6. Crack growth rate vs. stress intensity factor range



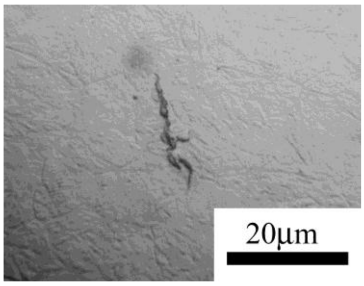
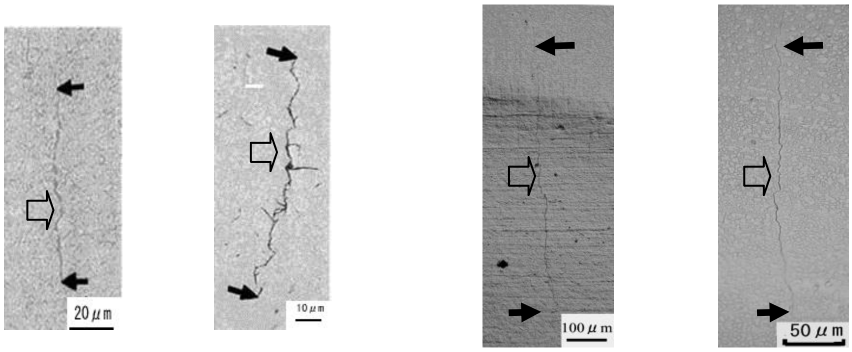


Figure 7. Cracks observed in Steel C in low (RH25%, left) and high (RH85%, right) humidity, respectively (Axial stresses applied in the horizontal direction)



(a) Steel A: RH 25%; RH 85% (b) Steel C: RH 25%; RH 85%

Figure 8. Crack morphology observed in (a) Steel A and (b) Steel C (Blank and solid arrows indicate origin of crack initiation and crack tips, respectively. Axial stresses applied in the horizontal direction)

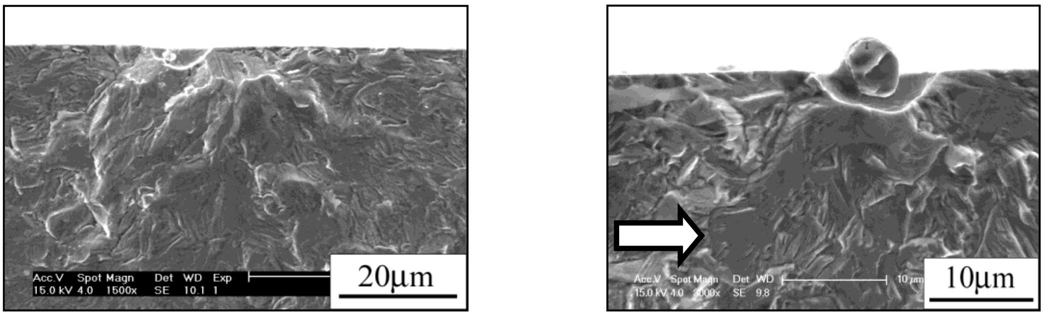


Figure 9. SEM micrographs showing fracture surfaces in RH25% (left) and RH85% (right) in Steel C

3.2 Effect of reverted austenite on fatigue properties in high humidity

Figure 10 shows the effect of reverted austenite on fatigue strength in different humidity by comparing the results of Steel B that had 10% reverted austenite with those of Steel A, which had the same hardness as Steel B but did not include any reverted austenite. Much different from that in Steel A, the fatigue strength of Steel B remains less affected by high humidity.

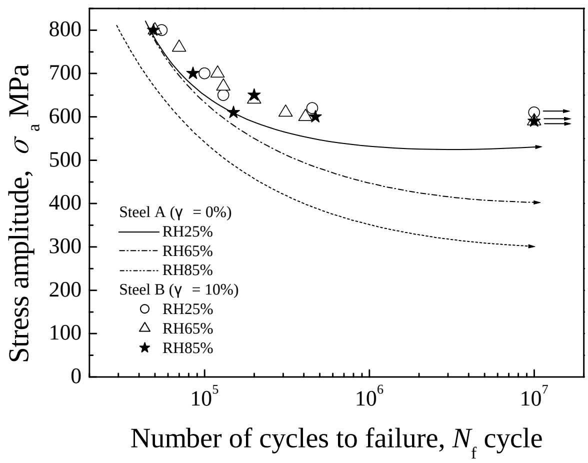


Figure 10. *S*-*N* curves of Steel B

The crack growth curve and the dependence of crack growth on stress intensity factor range in Steel B are shown in Figs. 11 and 12 respectively. As seen in Figs. 11 and 12, the effects of both humidity and reverted austenite on the propagation of small cracks are not distinguished in Steel B, though the crack initiation of Steel B is truly promoted by high humidity.

Further observation on crack morphology of Steel B fatigued in both low and high humidity reveals that the effect of humidity on macroscopic crack growth in Steel B is really limited, as shown in Fig. 13, implying that the reverted austenite in the matrix of Steel B does play an important role in the process of crack propagation [4], i.e. the widely distributed reverted austenite phases become trap sites of hydrogen [5, 6] and suppress the acceleration of crack propagation in high humidity due to hydrogen embrittlement.

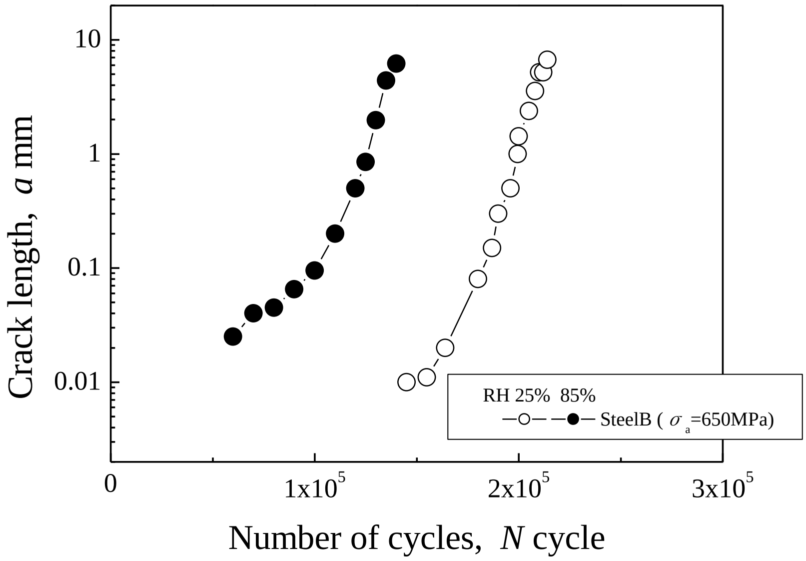


Figure 11. Crack growth curves of Steel B

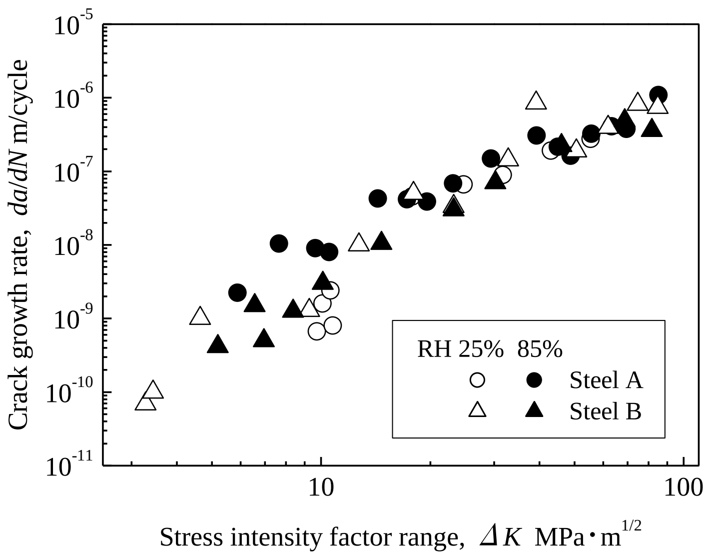
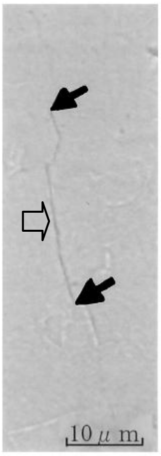
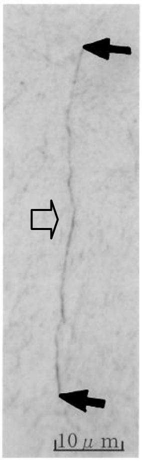


Figure 12. Crack growth rate vs. stress intensity factor range





(a) RH 25% (b) RH 85%

Figure 13. Crack morphology observed in Steel B (Blank and solid arrows indicate origin of crack initiation and crack tips, respectively. Axial stresses applied in the horizontal direction)

4. Conclusions

The effects of humidity and the aging structure on the 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 the humidity of RH50%. The main reason for the decrease in fatigue strength was the acceleration of both crack initiation and small crack growth. The propagation of larger cracks was not influenced by humidity. The promotion of crack initiation was due to anodic dissolution and the acceleration of crack propagation was caused by hydrogen embrittlement in accompany with cathode reaction. The hydrogen embrittlement assisted crack propagation was suppressed by the formation of reverted austenite.

Acknowledgements

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