Humid-sensitivity of fatigue strength of maraging steel and its improvement by shot peening

N. Kawagoishi [a], T. Nagano[b], Y. Kobayashi[c]
[a] Former Kagoshima University, Japan, nk-kawagoishi@outlook.jp
[b] Miyakonojo National College of Technology, Japan, takanori@cc.miyakonojo-nct.ac.jp
[c] Shinto Kogio, LTD., Japan, y-kobayashi@sinto.co.jp

Keywords: Fatigue, maraging steel, shot peening, humidity, hydrogen embrittlement, fish-eye fracture

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. However, the fatigue strength is very lower than expected from its static strength similar to other high strength steels. Main reasons for low resistance to fatigue are caused by their high susceptibilities for notch and humidity. For the reasons, many methods such as modifying microstructure, surface treatment and so on have been developed to improve fatigue properties of maraging steel. Shot peening is one of the useful technologies which is strengthened by hardening and compressive residual stress formed at the peened surface layer. However, studies about effect of corrosive environments on fatigue properties of maraging steel, especially effect of humidity on fatigue properties of shot peened one, were very limited in comparison with those about the resistance to stress corrosion cracking of the steel.

In the present study, rotating bending fatigue tests were carried out to investigate the effect of shot peening on humid-sensitivity in fatigue of maraging steel.

Material and experimental procedures

The material used was a 350 grade 18% Ni maraging steel whose chemical composition in mass % was 0.001C, 0.01Si, 0.01Mn, 17.89Ni, 4.27Mo, 12.36Co, 1.3Ti, 0.08Al, Bal. Fe. The steel was solution treated for 5.4ks at 1123K in vacuum, followed by air cooling and age hardened for 150ks at 753K and then for 400ks at 673K in a salt bath. Figure 1 shows aging curve and selected aged condition for fatigue test by mark ○. By the above stated double aging, further hardening was obtained over the peak aged condition in the single aging, i.e. conventional aging treatment of maraging steel. The mechanical properties of aged specimen were 0.2% proof stress of 2420 MPa, tensile strength of 2549 MPa, reduction of area of 51% and Vickers hardness of *HV* 785.

Figure 2 shows shape and dimensions of specimen. After machining the specimens, parts of the specimens were electro-polished by about 20μm from the surface layer and the rest were shot peened using steel shots of ϕ0.3mm with Vickers hardness *HV*900. The coverage was 300%. Fatigue tests were carried out using a rotating bending fatigue testing machine with a capacity of 15 Nm operating at about 50Hz in relative humidity environments of controlled 25% and 85%.

Results and discussion

Figure 3 shows distributions of hardness and residual stress in the shot-peened specimen. Marked hardening and compressive residual stress were generated at the surface layer of specimen by shot peening. The hardened depth is about 200μm, and the maximum value of compressive residual stress is about 900MPa where located at 50μm in depth, respectively. The surface roughness *R*y of the shot peened specimen was about 9.2μm.

Figure 4 shows *S-N* curves of the electro-polished specimen and the shot-peened one in both environments.

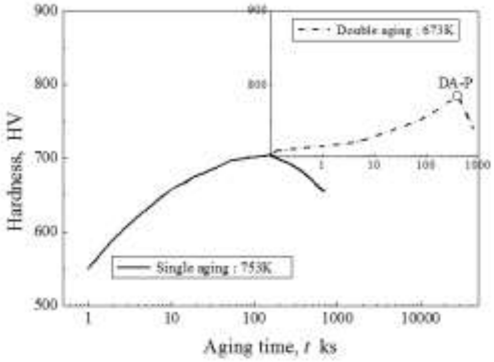


Figure 1 Aging curve

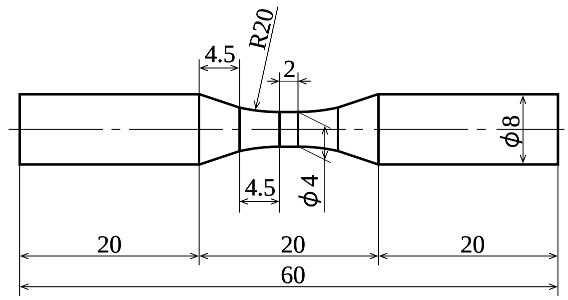


Figure 2 Shape and dimensions of specimen

Figures 5 and 6 show the typical fracture surfaces. All of the fractures occurred from a lath boundary cracking or a pit at the specimen surface in the electro-polished specimens. However, in the shot-peened specimens, fracture originated from the specimen surface in the short life region and an internal fracture occurred from the internal defect in the long life region. In addition, a combined fracture due to coalescence of both cracks originated separately from the specimen surface and its internal occurred in the middle life region between surface fracture and internal one. So, in Fig.4, the surface, the internal and the combined fractures are indicated by open, solid and semi-solid marks, respectively.

As seen from Figs. 4~6, fatigue strength was markedly increased by shot peening. Furthermore, the decrease in fatigue strength by high humidity was hardly confirmed in the shot-peened specimen, while the strength was largely decreased by high humidity in the electro-polished specimen. That is, shot peening is one of effective methods to improve both the fatigue strength and its humid-sensitivity. In connection with the effect of humidity on fatigue strength, there is no or little effect of humidity on fracture surface in the shot-peened specimen, while brittle facets are observed at the crack initiation site in high humidity in the electro-polished specimen. In general, *S-N* curves in high strength steels and surface treated steels show a duplex *S-N* shape [1]. However, the ones of the shot-peened maraging steel showed a monotonous increase in fatigue life with decreasing in stress level similar to the one in the electro-polished specimen. The difference in the shape of a *S-N* curve may be caused by the difference in transition of fracture mechanism. That is, an obvious change in fracture origin occurs from the specimen surface to its internal with decreasing in stress level in many high strength steels and surface treated ones, while there is the region of the combined fracture between the surface fracture and the internal one in the shot-peened maraging steel as mentioned avove.

In the following, the reason for that humid sensitivity of maraging steel was improved by shot peening will be investigated.

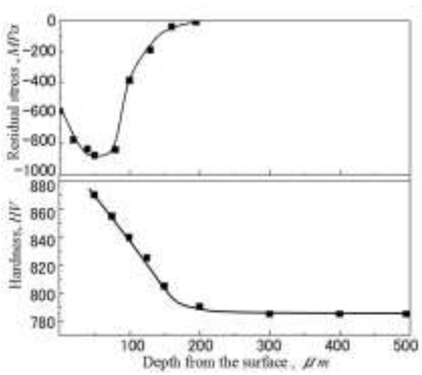


Figure 3 Distributions of hardness and residual stress of shot-peened specimen

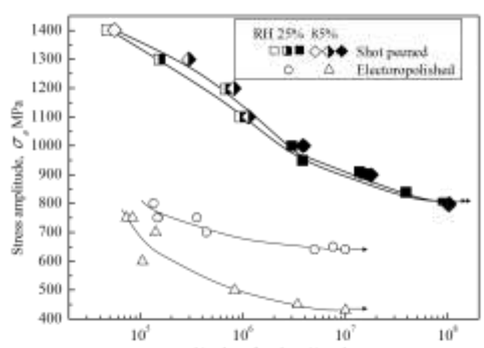
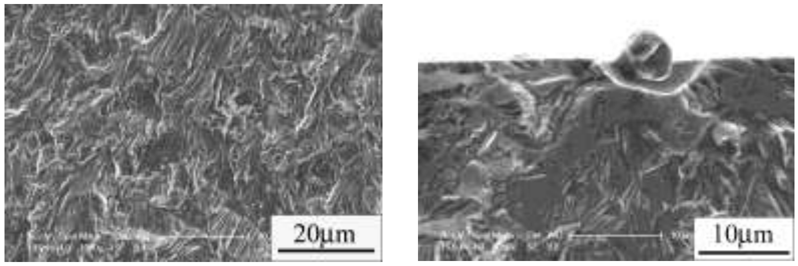
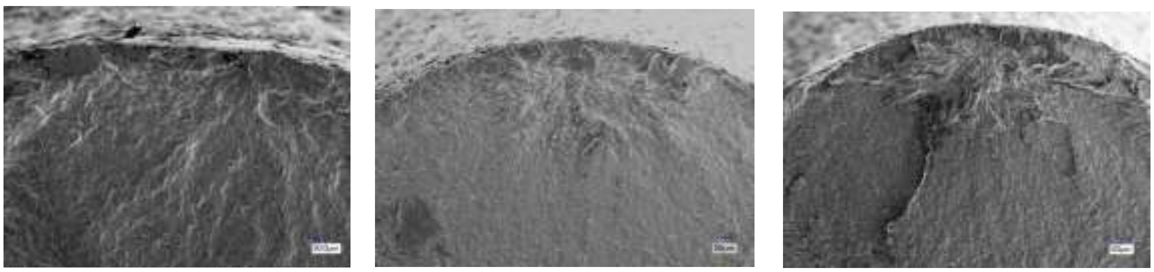


Figure 4 *S-N* curves of electro-polished and shot-peened specimens



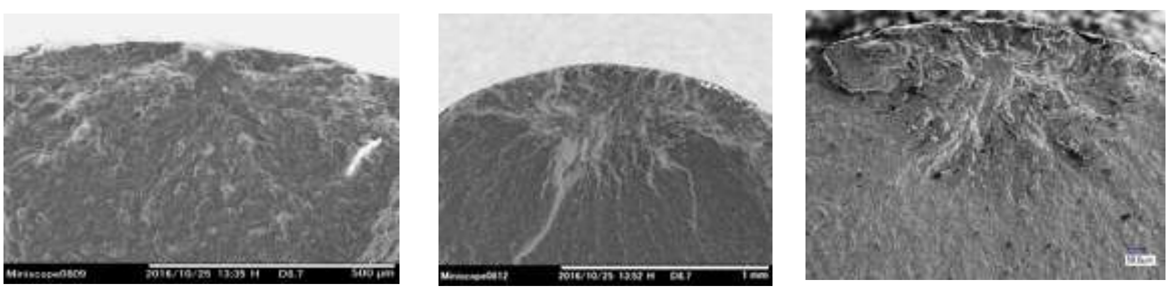
(a) RH25% (b) RH85%

Figure 5 Fracture surfaces of electro-polished specimens (σ_a= 750MPa).



(a-1) Surface fracture (σ_a= 1400MPa) (a-2) Internal fracture (σ_a= 900MPa) (a-3) Combined fracture (σ_a= 1000MPa)

(a) RH25%



(b-1) Surface fracture (σ_a= 1400MPa) (b-2) Internal fracture (σ_a= 900MPa) (b-3) Combined fracture (σ_a= 1000MPa)

(b) RH85%

Figure 6 Fracture surfaces of shot-peened specimens

Figure 7 shows the surface state of the electro-polished specimen observed at the fatigued specimen in high humidity. An obvious corroded pit and a few cracks initiated from the pit are confirmed at the specimen surface. Therefore, the decrease in fatigue strength by high humidity in the electro-polished specimen can be explained from the results in Figs.5 and 7, as follows: In high humidity, anodic resolution of the steel occurred in the corrosion reaction of the steel with water vapor in humid air and promoted the crack initiation. In addition, hydrogen atoms generated by the cathodic reaction in the corrosion process may diffuse into the matrix and induce hydrogen embrittlement, i.e. the acceleration of crack propagation. Now, we estimate the diffusion depth d_{Hs} of hydrogen into the matrix to confirm the effect of hydrogen in case of the condition shown in Fig.5 by using D_H=1.7× 10^{-13} m^2/s as diffusion coefficient of hydrogen in the maraging steel [2]. In this case, the crack initiation life was confirmed as about 2× 10^4 cycles by a success observation of specimen surface at fatigue process. This life can be converted to t=400s (t: exposure time in high humidity) under the loading frequency 50Hz. Consequently, we get $d_{Hs} \approx \sqrt{(D_H t)} \approx 10\mu m$. This value nearly corresponds to the depth of brittle facet shown in Fig.5, suggesting that the acceleration of crack propagation may be caused by hydrogen embrittlement.

On the other hand, the reason for that there is no or little effect of humidity on the fatigue strength

in the wide life region including the surface fracture in the shot-peened specimen may be explained from viewpoints of both the compressive residual stress and the change in fracture mechanism by shot peening. Some studies on the internal fracture reported that the environment surrounding an internal crack is nearly vacuum environment. If so, fatigue strength is not influenced by humidity. However, hydrogen generated at around the specimen surface can diffuse into the matrix through the lattice diffusion, transportation by dislocations and so on as mentioned above. Then, we estimate the diffused depth of hydrogen in long life region where the internal fracture occurs. There is a study reported that an internal crack initiated at the early stage of fatigue process, for example crack initiation life N_i was about 10^4 cycles for fatigue life N_f of 10^7 cycles in quenched and tempered SCM 435 steel (HV550) [3]. The authors also reported that a crack initiated at the early stage of fatigue process and most fatigue life was occupied by the growth life of a crack smaller than 100μm in nitride bearing steel SUJ2 [4]. Referring to these studies, the diffused depth of hydrogen d_{Hi} in the present steel can be estimated as d_{Hi}≈60μm for N_i =10^6 cycles (t=20ks), where the fatigue life N_f is assumed as 10^7 cycles and N_i/N_f =0.1, as example.
Figure 8 shows the depth of a crack origin of the internal fracture, d_{inc}, in the shot-peened specimen. Mean value of d_{inc} is about 150μm, meaning that the crack initiation site is deeper than the affected zone by hydrogen. That is, the effect of hydrogen is no or little on the initiation and the early propagation of the internal crack.
The above mentioned consideration suggests that fatigue strength in the regions of the surface fracture and the combined one may be influenced by high humidity similar to the result of the electro-polished specimen, because their fatigue lives include a growth process of a surface crack. However, there was no effect of humidity on the fatigue strength even in the regions (Fig.4). This can be explained from that the crack growth and hydrogen embrittlement were suppressed by compressive residual stress, because the depth of a surface crack affected by hydrogen (Fig.5) nearly corresponds to the layer of compressive residual stress. Actually, any brittle facets were not observed at the fracture surface around a crack initiation site as shown in Fig.6(b-1) and (b-3).

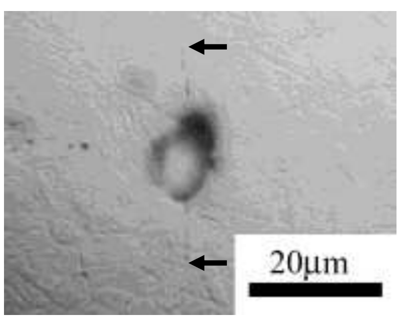


Figure 7 Surface state of electro-polished specimen after fatigue in high humidity (arrow indicates crack tip)

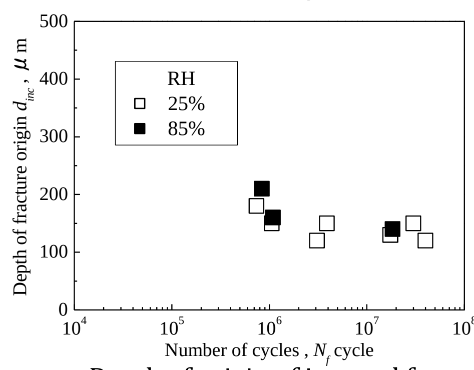


Figure 8 Depth of origin of internal fracture in shot-peened specimen

Summaries

It was shown that shot-peening was one of effective technologies to improve not only the fatigue strength but also the humid-sensitity of maraging steel. These results were explained from viewpoints of both compressive residual stress caused by shot peening and the effect of hydrogen generated by corrosion reaction of the steel with water vapor in humid air.

References

[1] Shiozawa, K. et al., *Jour. of Soc. of Mater. Sci., Japan*, Vol. 48, 1095, 1999
[2] Bond B.G., Acta Metallurgica et Materialia, Vo. 38, 2373, 1990
[3] Kuroshima, Y. et al., *Trans. Japan. Soc. Mech. Eng. A*. Vol.60, 2710, 1994
[4] Kawagoishi, N., et al., *Trans. Japan. Soc. Mech. Eng. A*. Vol.71, 1362, 2005