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Effects of Reverted Austenite and Hardness on Fatigue Properties of Shot Peened Maraging Steel in Long Life Region

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Abstract: In the present study, rotating bending fatigue tests up to 10^8 cycles were carried out to investigate the effects of hardness of base steel and shot and reverted austenite, γ, on the fatigue strength and the fracture mechanism in wide range of fatigue life of shot peened 3.5GPa-grade maraging steel. By shot peening, hardening and compressive residual stress were yielded in the surface layer of specimen, causing increase in fatigue strength in the wide region of fatigue life. The $S-N$ curves showed duplex $S-N$ properties because of the transition of fracture origin from the specimen surface in the short life region to the subsurface in the long life one. The effect of hardness of base steel on fatigue strength was very small in both regions of the surface and subsurface fractures. On the other hand, fatigue strength in surface fracture region was increased by using hard shot. By formation of γ, fatigue strength was increased in the subsurface fracture region, but the effect was not recognized in the surface fracture region. A clear fish-eye was formed around the origin of subsurface fracture in the steel withγ, though it was not observed in the steel withoutγ.

Keywords: Fatigue, maraging steel, rotating bending, hardness, reverted austenite, surface fracture, subsurface fracture

1 Introduction

Many high strength metals have been used as materials for machines and components operating under heavy loads in order to answer the demands for weight reduction and long-term service which leads to reducing environment load. Maraging steel is an ultra-high strength steel which is hardened by the precipitation of

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intermetallic compounds in martensitic structure [Marder and Marder (1969)]. The steel has both of the highest tensile strength and high ductility among practically used steels. However, the fatigue strength, which is the most important property for structural steels, is very low in compared with its high static strength similar to other high strength steels. This is caused by their high sensitivities for notch and humidity [Murakami and Shimizu (1983), Endo and Komai (197)]. Therefore many studies have been carried out to investigate the improvement methods of fatigue properties, e.g., surface treatments such as shot peening [Nagano, Kawagoishi and Moriyama (2003)] and nitriding [Kawagoishi, Morino, Fukada, Kondo and Yan (2003)], heat treatments, and so on.

In the present study, effects of hardness of base steel and shot and reverted austenite, γ, on the fatigue strength and the fracture mechanism of shot peened 3.5GPa-grade maraging steel were investigated to improve fatigue strength by shot peening in wide life region.

2 Material and Experimental Procedure

The material used was an 18% Ni maraging steel (3.5 GPa-grade) whose chemical composition in mass % was 0.001C, 0.01Si, 0.01Mn, 17.89Ni, 4.27Mo, 12.36Co, 1.3Ti, 0.08Al and remainder Fe. The material was solution treated for 5.4ks at 1123K in vacuum, followed by air cooling and age hardened at different conditions shown in Figure1 in a salt bath.

Figure 1 shows aging curves. In the figure, round and square marks mean aging conditions selected for fatigue tests in the present study. The mechanical properties of aged specimens were shown in Table 1.

Figure 2 shows shape and dimensions of specimen. After machining the specimens, the parts were electro-polished by about 20μÌm from the surface layer and the rest were shot peened under the conditions shown in Table 2. Distributions of hardness and residual stress were measured by using a micro Vickers hardness tester (1.97N) and an X ray diffraction device (Cr-£ËαÁ), respectively. Fatigue tests were carried out using a rotating bending fatigue testing machine operated at about 50Hz in ambient atmosphere, where relative humidity (RH) was about 50-70%.

3 Experimental Results and Discussion

3.1 Surface integrities of shot peened specimen

Figures 3 and 4 are distributions of hardness and residual stress in shot-peened specimens showing the effects of hardness of base steel and γ, respectively. Marked hardening of surface layer was generated in all steels. The harder steel is, the larger

Table 1: Mechanical properties

aging condition	0.2% Proof strength $\sigma_{0.2}$(MPa)	Tensile strength σ_B(MPa)	Hardness HV	Elongation δ(%)	Reduction of area, ψ (%)
843K - 2ks	2190	2105	660	10.9	54
813K - 2ks	2200	2140	660	10.2	53
753K - 150ks	2310	2260	705	8.3	54

Table 2: Shot peening conditions

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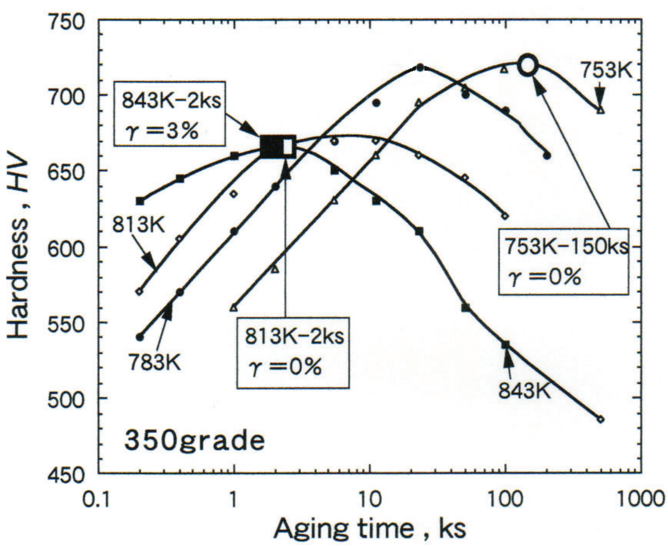


Figure 1: Aging conditions

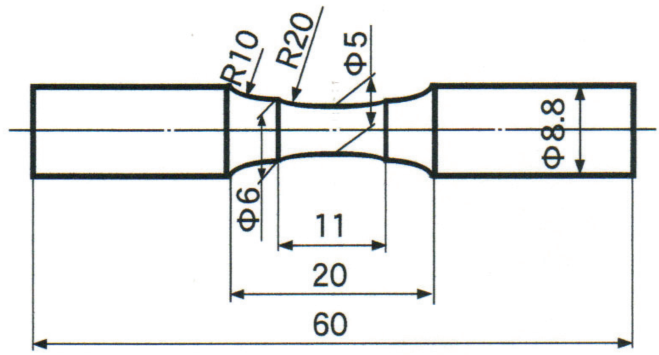


Figure 2: Shape and dimensions of specimens

the surface hardness is, though the difference in the hardened depth and the effect of reverted austenite are hardly observed. Moreover, compressive residual stress was generated by shot peening in all of the shot peened specimens and the maximum values of the stresses are higher in the steels with low hardness and without reverted austenite, though the depth at the point are nearly the same.

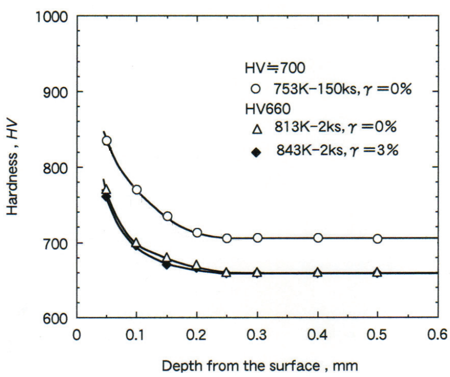


Figure 3: Distribution of hardness of shot peened specimens(Effects of hardness of base steel, HV660&700 and reverted austenite, γ=0&3%)

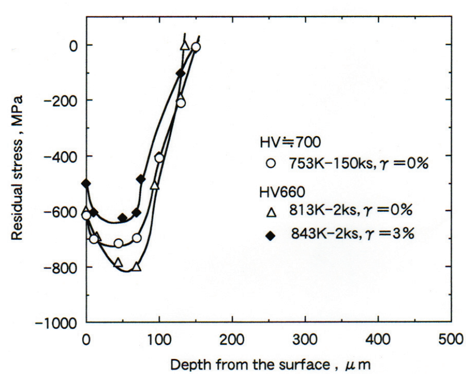


Figure 4: Distribution of residual stress of shot peened specimens (Effects of hardness of base steel, HV660&700 and reverted austenite, γ=0&3%)

Figure 5 shows surface roughness of shot peened specimen. The surface roughness was higher in the steel with low hardness and with reverted austenite.

Figures 6, 7 and 8 are distributions of hardness, residual stress and surface roughness in shot-peened specimens showing the effect of hardness of shot. Large in-

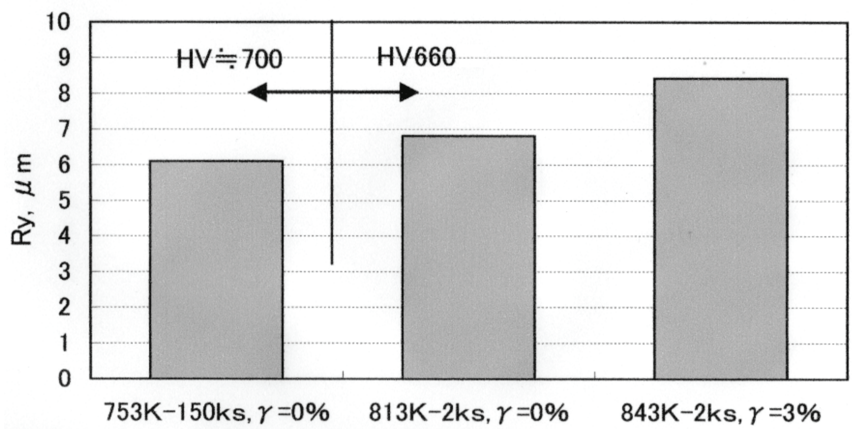


Figure 5: Surface roughness of shot peened specimens (Effects of hardness of base steel, $HV660\&700$ and reverted austenite, γ=0&3%)

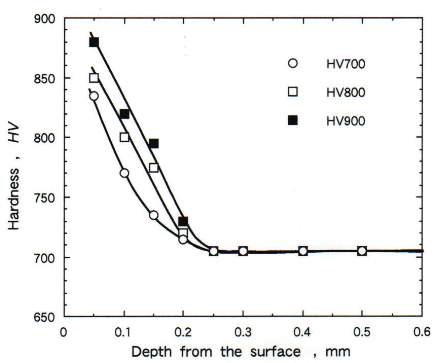


Figure 6: Distribution of hardness of shot peened specimens (Effect of hardness of shot, $HV700$, 800&900)

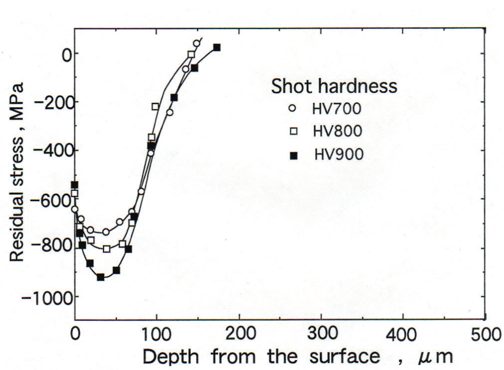


Figure 7: Distribution of residual stress of shot peened specimens(Effect of hardness of shot, $HV700$, 800&900)

creases in surface hardening and compressive residual stress are yielded by using hard shot, though the surface roughness was increased.

3.2 Fatigue strength of shot peened specimen

3.2.1 Effect of hardness of base steel on fatigue strength

Figure 9 shows $S-N$ curves for two kinds of shot-peened specimens with different hardness of base steel, i.e. $HV660$ and $HV700$. In the figures, open marks and solid

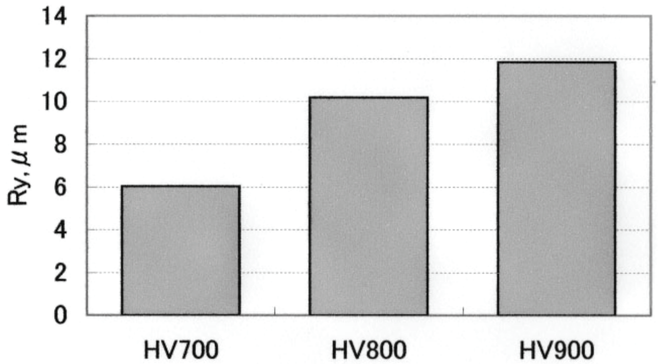


Figure 8: Surface roughness of shot peened specimens (Effect of hardness of shot, $HV700$, 800&900)

ones mean a surface fracture and a subsurface one, respectively as shown in Fig.10. That is, in all of shot-peened specimens, fracture originated from the specimen surface in the short life region and an internal fracture occurred from the subsurface in the long life region, while only surface fracture occurred from specimen surface in electro-polished specimens in wide life region. Fatigue strength was increased markedly by shot peening, while the increase in fatigue strength was small in long life region. $S-N$ curves of shot peened specimens show duplex $S-N$ shape similar to the ones of many high strength steels and surface treated steels [Oguma, Harada and Sakai (2003), Takeuchi, Matsuoka, Okita and Hori (2005)]. However, the horizontal line in $S-N$ curve, which corresponds to the fatigue limit for surface fracture, is not clear. There is no or little influence of hardness of base steel on fatigue strength not only in surface fracture region but also in subsurface fracture one.

As well known, though the hardening of specimen surface suppresses the crack initiation, the increase in surface roughness makes it easier, and the harder the surface layer, the larger the notch effect. On the other hand, compressive residual stress suppresses the crack propagation [Tange, Akutsu and Takamura (1991)]. In considering the effects of shot peenig on the surface integrities mentioned above, the effect of shot peening on the fatigue strength shown in Fig, 8 can be explained as follows. That is, the initiation of a crack is early in the steel with low hardness due to high roughness, but the propagation is suppressed by large compressive residual stress in short life region. On the other hand, the initiation of a crack from an inclusion is early in harder steel due to high notch sensitivity, but the propagation is suppressed because of high compressive stress in long life region. That is, opposite

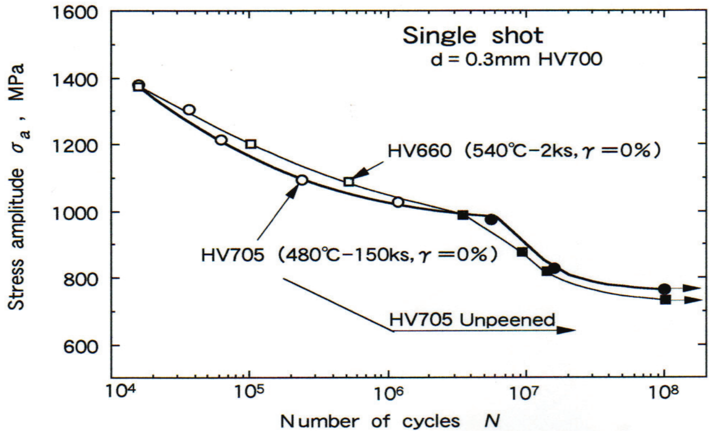
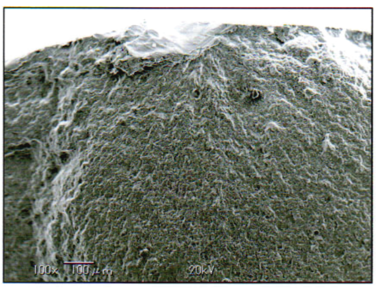
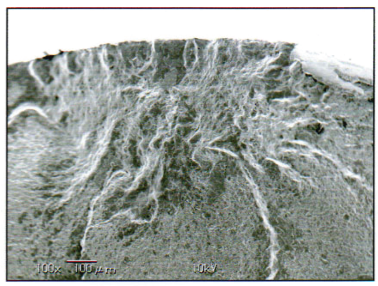


Figure 9: $S-N$ curves of shot peened specimens(Effect of hardness of base steel, HV660&700)

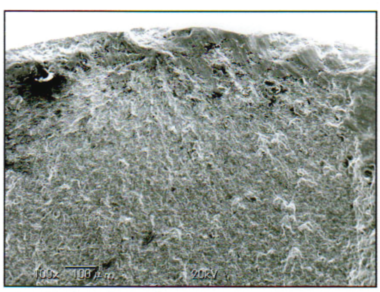


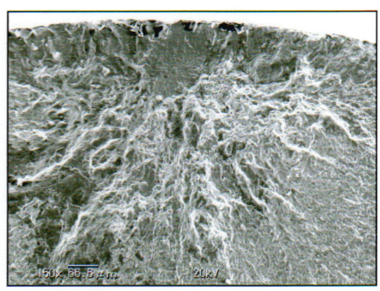


(a-1) Surface fracture (σ_a=1200MPa, N=1.2×10^5)

(a-2) Internal fracture (σ_a=850MPa, N=1.5×10^7)

(a) HV 660





(b-1) Surface fracture (σ_a=1200MPa, N=6.3×10^4)

(b-2) Internal fracture (σ_a=800MPa, N=1.7×10^7)

(b) HV 700

Figure 10: Fracture surfaces (Effect of hardness of base steel, HV660&700)

effects of the promotion of a crack initiation by notch effect and the suppression of crack propagation by compressive residual stress on fatigue life cancel each other.

3.2.2 Effect of reverted austenite on fatigue strength

Figure 11 shows $S-N$ curves for shot peened specimens with reverted austenite and those without one.

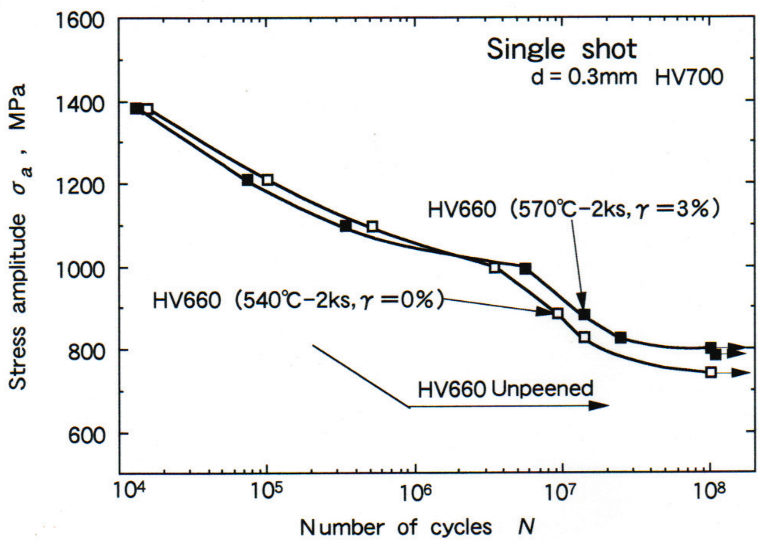
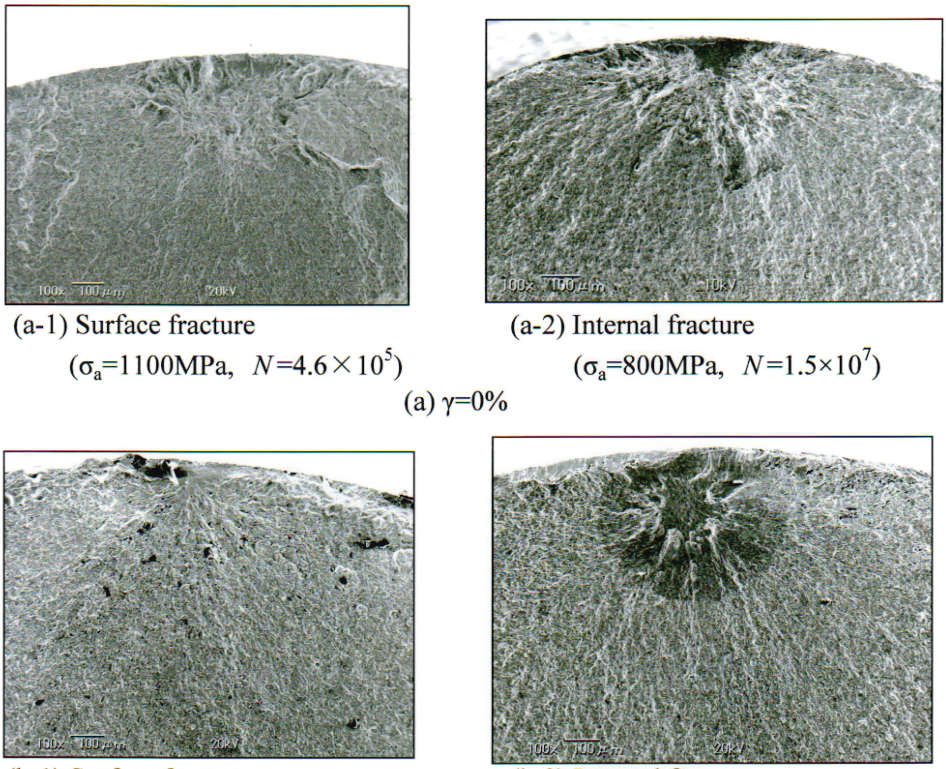


Figure 11: $S-N$ curves of shot peened specimens (Effect of reverted austenite, γ=0&3%)

Figure 12 shows fracture surfaces. The feature of $S-N$ curves and the change in fracture origin from specimen surface to the subsurface with decreasing in stress levels are similar to the one shown in Fig.9. Fatigue strength is larger in the steel with reverted austenite than in the one without reverted austenite in the subsurface fracture region, though the difference in fatigue strength is hardly recognized in surface fracture region. No difference in fatigue strength in surface fracture region may be explained from the opposite effects of surface roughness and compressive residual stress on fatigue strength. On the other hand, in the subsurface fracture region, though there is no difference in crack initiation life regardless of reverted austenite because of the same hardness, the compressive residual stress is large in the steel with reverted austenite,

causing the suppression of crack propagation. Moreover a clear fish-eye is observed in the steel with reverted austenite, but it do not in the steel without one in



(a-1) Surface fracture (σ_a=1100MPa, N=4.6×10^5)

(a-2) Internal fracture (σ_a=800MPa, N=1.5×10^7)

(a) γ=0%

(b-1) Surface fracture (σ_a=1200MPa, N=7.6×10^4)

(b-2) Internal fracture (σ_a=800MPa, N=2.4×10^7)

(b) γ=3%

Figure 12: Fracture surfaces (Effect of reverted austenite, γ=0&3%)

the subsurface fracture region as shown in Figure 12, and the decrease in intergranular cracks and the increase in transgranular cracks are obviously observed around the fracture origin. This means that the life of steady growth of a crack increased. Consequently, fatigue life was increased by formation of reverted austenite in subsurface region, because fatigue life for subsurface fracture is mainly occupied by the lives for crack initiation and propagation of a small crack [Kawagoishi, Morino, Tajiri, Chen, Wang and Fukada].

3.2.3 Effect of hardness of shot on fatigue strength

As mentioned above, fatigue strength of shot peened steel is improved by formation of reverted austenite in the subsurface region, but it is difficult to improve fatigue

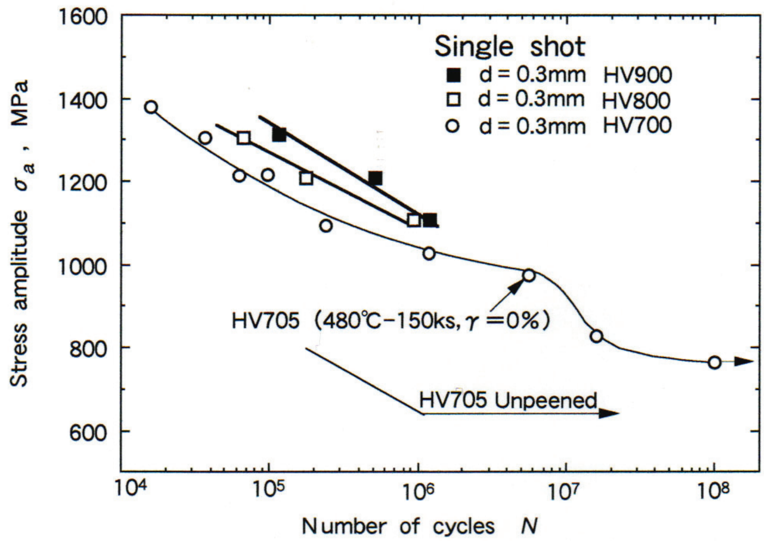


Figure 13: $S-N$ curves of shot peened specimens (Effect of hardness of shot, $HV700$, 800 &900)

strength in surface fracture region. Surface hardening is effective to suppress the crack initiation and compressive residual stress to the crack propagation. These effects suggest that fatigue strength in surface fracture region may be increased by shot peening using hard shot from the results shown in Figures 6 and 7.

Figure 13 is $S-N$ curves of shot peened specimens showing the effect of hardness of shot on fatigue strength in surface fracture region. Fatigue strength was largely increased by hard shot.

Form the results mentioned above, fatigue strength can be improved by shot peening in combination of use of hard shot and formation of reverted austenite in wide life region.

4 Conclusions

By shot peening, hardening and compressive residual stress were yielded in the surface layer of specimen, causing increase in fatigue strength in the wide region of fatigue life. The $S-N$ curves showed duplex $S-N$ properties because of the transition of fracture origin from the specimen surface in the short life region to the subsurface in the long life one. Fatigue strength of shot peened steel is improved by formation of reverted austenite in the subsurface region, and by using hard shot in surface fracture region.

References

Endo, K.; Komai, K. (1977): Fatigue crack growth of aluminum alloy in ultra-high vacuum, *Journal of the Society of Materials and Science, Japan*, vol.26, pp.143-148.

Kawagoishi, N.; Morino, K.; Fukada, K.; Kondo, E.; Yan, N. (2003): Influence of nitriding condition on fatigue strength of maraging steel, *Journal of the Society of Materials and Science, Japan*, vol.52, pp.1331-1336.

Kawagoishi, N.; Morino, K.; Tajiri, Y.; Chen, Q.; Wang, QY.; Fukada, K. (2005): Propagation behavior of an internal crack of a radical nitrided bearing steel, Trans. *Transaction of Japan Societies for Mechanical Engineers A*, vol.71, pp.1362-1368.

Marder, J.M.; Mareder, A.R. (1969): The morphology of iron-nickel massive martensite, *Transaction of ASM*, vol.62, pp. 1-10.

Murakami, Y.; Shimizu, M. (1988): Effects of non-metallic inclusions, smack defects and small cracks on fatigue strength of metals, *Transaction of Japan Societies for Mechanical Engineers A*, vol.54, pp.413-425.

Nagano, T.; Kawagoishi, N.; Moriyama, M. (2003): Influence of reversion austenite on initiation and propagation of fatigue crack of maraging steel, *Transaction of Japan Societies for Mechanical Engineers A*, vol.69, pp.633-639.

Oguma, N.; Harada, H.; Sakai, T. (2003): Mechanism of long life fatigue fracture induced by interior inclusion for bearing steel in rotating bending, *Journal of the Society of Materials and Science, Japan*, vol.52, pp.1292-1297.

Takeuchi, E.; Matsuoka, S.; Okita, K.; Hori, H. (2005): Effect of shot peening on fatigue properties for alloy 718 nickel based superalloy, *Transaction of Japan Societies for Mechanical Engineers A*, vol.71, pp.1051-1057.

Tange, A.; Akutsu, T.; Takamura, N. (1991): Relation between shot-peening residual stress distribution and fatigue crack propagation life in spring steel, *Bane Ronbunshu,* vol.36, pp.47-53.