Transactions on Engineering Sciences vol 33, © 2001 WIT Press, www.witpress.com, ISSN 1743-3533

Influence of Radical Nitriding on Fatigue Strength of Maraging Steel

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Abstract

Rotating bending fatigue tests were carried out to investigate the influence of radical nitriding on surface integrity and fatigue strength for a maraging steel. Fatigue strength was increased by nitriding. The initiation site of fracture was the surface at high stress levels and the interior at low stress levels in a nitrided steel, though it was the surface at all the stress levels in an aged steel. Consequently, S-N curve of the nitrided steel showed a double staged one, though that of the aged steel was an ordinary S-N one. In the nitrided steel, the main reason for the suface fracture was surface embrittlement while the one for the interior fracture was surface hardening, due to nitriding.

1 Introduction

Maraging steel has both high static strength and ductility. The fatigue strength, however, is low for its high static strength[1]. This is mainly caused from the high notch sensitivity and the presence of inclusions in the material[2]. Therefore, many studies have been carried out to improve the fatigue strength from view points of the strengthening of microstructure and the surface modification. However, it was reported that the fatigue strength can be increased[3], or not affected or decreased inversely[4,5] by surface modification, depending on the combination of material and modification method. For example, the surface modification by shot peening[6] or nitriding[7-9] was successful for improvement of fatigue strength of a maraging steel. Among many nitriding methods, radical nitriding is a new and attractive surface modification technology because of its high quality and pollution-free process [10].

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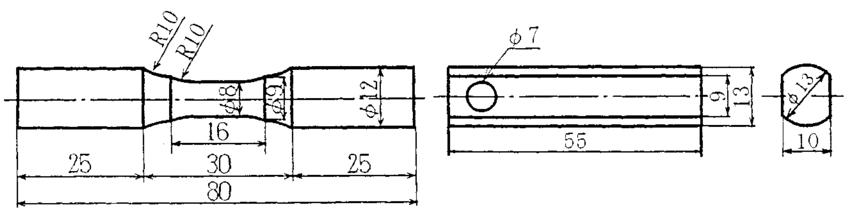
In the present study, rotating bending fatigue tests were carried out to investigate the influence of radical nitriding on the surface integrity and the fatigue strength in a maraging steel.

2 Material and experimental procedures

The material used was a 300 grade maraging steel whose chemical composition in weight percent was 0.005C, 0.03Si, 0.04Mn, 0.002S, 18.69Ni, 4.89Mo, 8.92Co, 0.10Al, 0.91Ti and remainder Fe. The material was solution treated by heated at 820°C for 1 h and air cooled, then aged at 490°C for 5 h followed by furnace cooling.

Figure 1 shows the shape and dimensions of specimens. Figures 1(a) and 1(b) are for fatigue tests and measurements of hardness and residual stress, respectively. After machining, all the specimens were electro-polished by about 20 μm from the surface layer. Radical nitriding was performed after electro-polishing by heating the specimen at 480°C for 1 h in H_2 gas and then nitriding at 480°C for 5 h in NH_3 gas followed by furnace cooling. Measurements of hardness and residual stress were performed using Vickers hardness tester and X ray diffractmeter, respectively. Fatigue tests were performed at room temperature using the Ono type rotating bending fatigue testing machine with capacity of 100 N · m operating at 55Hz.



(a) Specimen for fatigue test

(b) Specimen for measurements of hardness and residual stress

Figure 1: Shape and dimensions of specimens.

3 Experimental results and discussion

3.1 Influence of nitriding on surface integrity and mechanical properties

Figures 2(a) and 2(b) show distributions of hardness and residual stress in the nitrided steel. The marked hardening and the formation of compressive residual stress are observed in the surface layer. The depth of the affected layer, case depth, is about 80 μm.

Figure 3 shows the results of element analysis of nitrided specimen surface. Compounds of $Fe_{2.5}N$ and Fe_3NiN are observed. The formation of compound in addition to diffusion of nitrogen may contribute to the hardening of surface layer.

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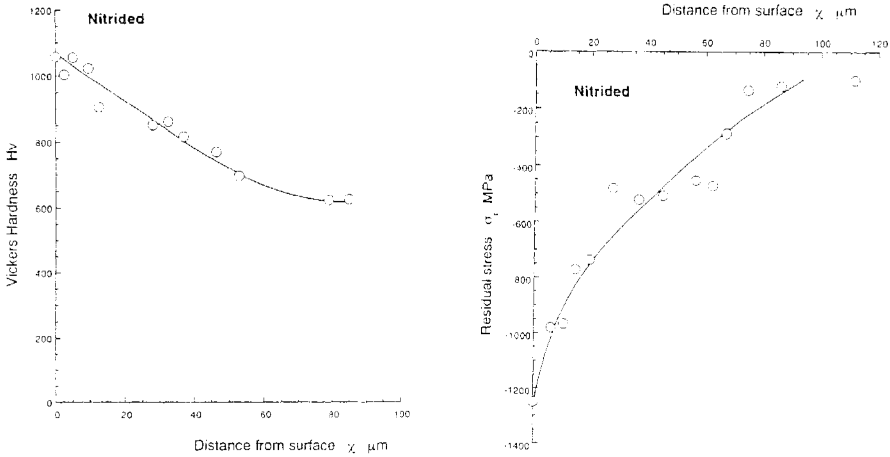

(a) Hardness distribution (b) Residual stress distribution

Figure 2: Distributions of hardness and residual stress.

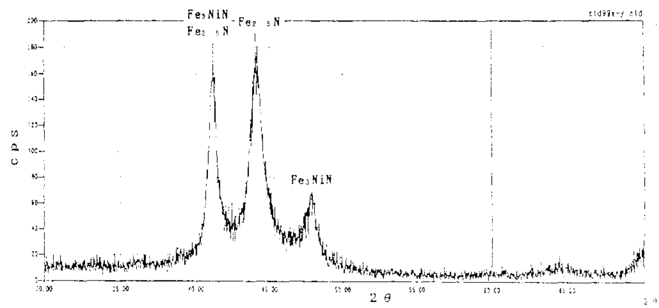

Figure 3: X-ray diffraction pattern of nitrided steel.

The mechanical properties of aged steel are 2020 MPa in 0.2% proof stress, 2090 MPa in tensile stress, 54.3 % in reduction of area and 630 in Vickers hardness, and those of nitrided steel are 2150 MPa in 0.2% proof stress, 2165 MPa in tensile stress, 31.5 % in reduction of area and 1050 in Vickers hardness, respectively. By nitriding, the ductility is decreased though the change in static strength is small.

Figure 4 is SEM photographs showing surface states of the aged and the nitrided steels. Many slip bands are observed in aged steel but brittle cracks in the nitrided one.

Figure 5 shows fracture surfaces of the aged and the nitrided steels. Although typical ductile fracture occurs in the aged steel, intergranular cracks are observed in the nitrided steel and these facts correspond to the results of surface observation.

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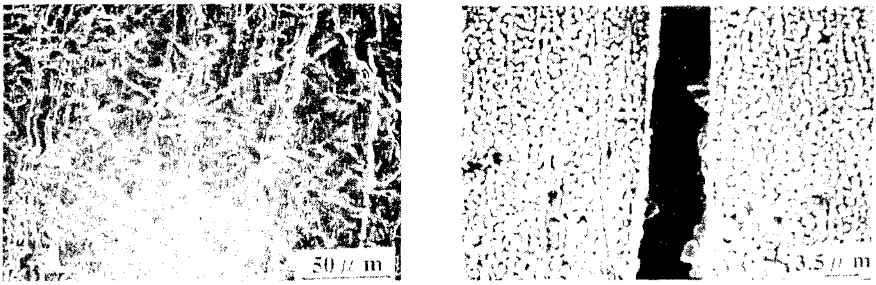
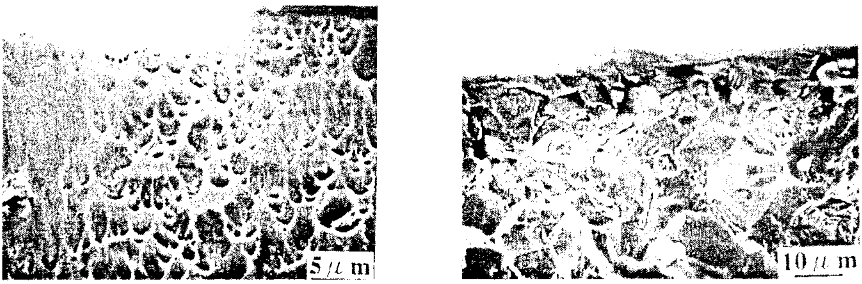


(a) Aged steel (b) Nitrided steel

Figure 4: Surface state of specimen after tensile test.



(a) Aged steel (b) Nitrided steel

Figure 5: Fracture surface of specimen after tensile test.

3.2 Influence of radical nitriding on fatigue strength

Figure 6 shows S-N curves of the aged and the nitrided steels. Fatigue strength is increased by nitriding and the increasing rate is larger at lower stress levels. The slash marks indicate subsurface fracture, i.e. fish-eye fracture. Fracture mode changes from the surface fracture in the short life region to the subsurface fracture in the long life region. Consequently, the shape of S-N curve in the nitrided specimen shows a double staged one which is similar to those found in the high strength steel[11] and the surface hardened steel[6,9], and the presence of fatigue limit is unclear till 10^7.

Figure 7 shows surface cracks in the aged and the nitrided steels at higher stress levels. Although all aged steels fractured from either surface crack or inclusion irrespective of stress levels, surface crack was observed only at higher stress levels not at lower stress levels in the nitrided steel. There is a difference in the morphology of cracks between the aged steel and the nitrided steel. That is, it is ductile in the aged steel and brittle in the nitrided one. This feature is similar to the one in tensile test shown in Figs. 4 and 5. That is, a hard surface layer is formed by nitriding, which fractured brittlely at high stress levels and the surface brittle crack promotes the crack initiation in the matrix due to notch effect.

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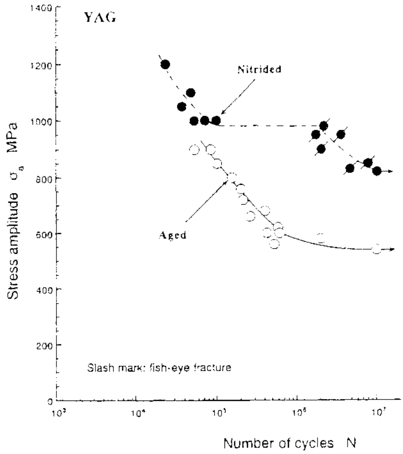
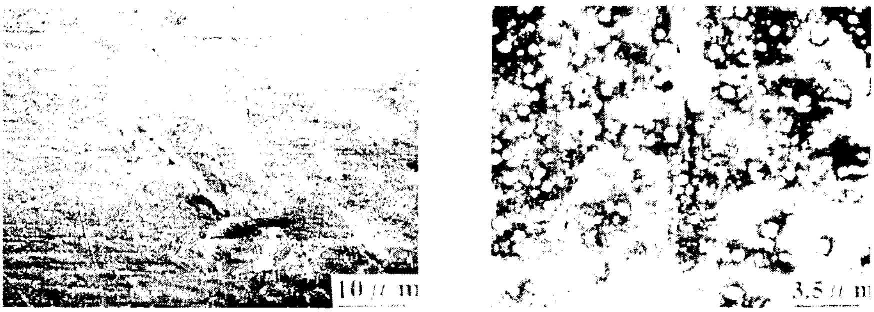


Figure 6: S-N curves.



(a) Aged steel (σa=800MPa) (b) Nitrided steel (σa=1100MPa)

Figure 7: Typical surface crack

Figure 8 shows fracture surface of the aged steel.

Figure 9 is a SEM photograph showing the fracture surface of the nitrided steel tested at lower stress level. Fracture originates from an inclusion at subsurface. The size of inclusion is about 10 μm. The border of fish-eye oriented to the specimen surface was located at interior, though it is not clear. This means that the growth of a crack is suppressed by the hardening and the formation of compressive residual stress in the affected layer. When the interior crack grew into a surface one, it propagated rapidly in the hard and brittle layer. Consequently, the border of fish-eye oriented to the surface is not clear, though the one oriented to the specimen center is clear and the feature of fracture is ductile.

Figures 10(a) and 10(b) are SEM photographs showing fracture surfaces where a fatigue crack propagated after the formation of fish-eye and the final fracture occurred statically. An intergranular cracking is observed in the hardened layer adjacent to dimple

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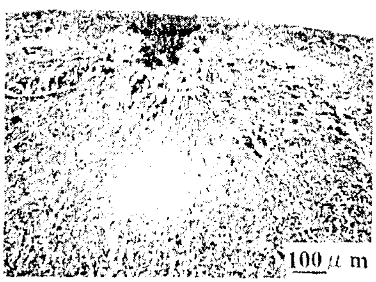
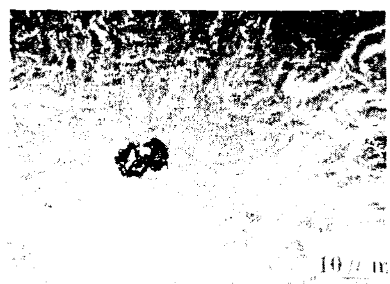
fracture in the non-hardened layer in the final fracture region. This also supports that the surface layer was embrittled after nitriding, though striations were observed in the fatigue region.

Figure 8: Fracture surface of aged steel (σa=800MPa).



(a) Fish-eye fracture



(b) Magnification of (a)

Figure 9: Fish-eye fracture of nitrided steel at low stress level (σa=840MPa).

Figure 11 shows the illustrated S-N curves indicating the influence of nitriding, as stated above. The dotted line is an assumed one for the strengthened steel by nitriding. The fatigue strength in the nitrided steel is increased due to hardening and formation of compressive residual stress in the surface layer.

However, it is decreased inversely under high stress levels owing to the embrittlement of hardened surface layer. As a result, the increase of fatigue strength is small at high stress levels. This means that nitriding should not be applied to maraging steel subjected to high cyclic loading. On the other hand, at low stress levels, fractures originated from internal inclusions, because the initiation of surface cracks were suppressed by surface hardening. Consequently, S-N curve of the nitrided steel shows a double staged one.

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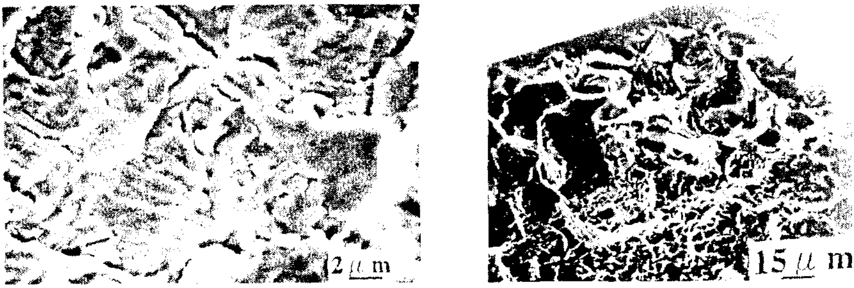

(a) Outer side of fish-eye (b) Final fracture site

Figure 10: Fracture surface of nitrided steel.

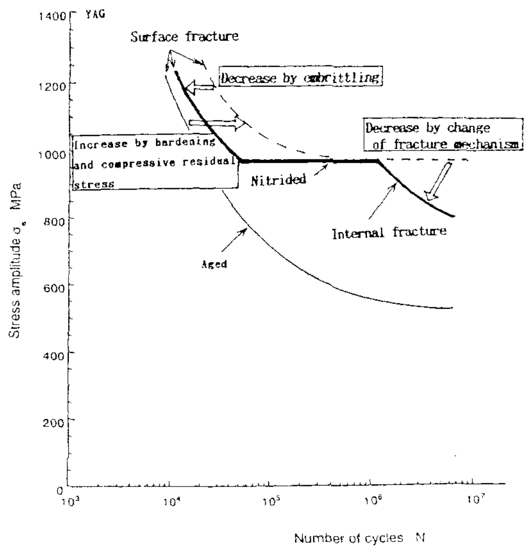

Figure 11: Influence of nitriding on fatigue strength of maraging steel.

4 Conclusions

The influence of radical nitriding on the fatigue strength of a maraging steel was investigated under rotating bending. Main results were summarized as follows.

The surface layer of the nitrided specimen was hardened and the compressive residual stress was produced by nitriding. Consequently, the surface layer became brittle whereas the static strength was hardly changed. On the other hand, fatigue strength was increased by nitriding, especially in the long life region. Although the initiation site of fracture was at the surface in the non-nitrided steel, i.e. in the aged steel, it was at the specimen surface at high stress levels and at the interior at low stress levels in the nitrided steel. The main reason for the surface fracture was the surface brittle cracking induced

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fatigue crack initiation, where-as the one for the interior fracture was the suppressions of surface slip and crack initiation due to the surface hardening. As a result, S-N curve of the nitrided maraging steel showed a double staged curve.

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