Effect of shot peening on fatigue strength of maraging steel

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Abstract

Rotating bending fatigue tests were carried out for a shot-peened maraging steel in order to investigate the effects of shot peening on the fatigue strength and the fracture mechanism focusing on the effect of surface roughness. Fatigue strength was markedly improved by shot peening because of hardening and generation of compressive residual stress in the surface layer. The origin of fatigue fracture changed from the specimen surface at high stress levels to an inclusion in the interior of specimen at low stress levels. And at the middle stress levels, both fracture modes were observed. Consequently, the shape of the S-N curve of shot-peened specimen was complex, corresponding to the change of fracture mode. In the region where surface fracture occurs, polishing the specimen surface and double shot peening using superhard fine particles were effective to improve the fatigue strength through the decrease in stress concentration due to smoothening the specimen surface.
1. Introduction

Maraging steel is an ultra-high strength steel which has both high tensile strength and high ductility [1],[2]. However, fatigue strength is relatively low in comparison with the high static strength [3]. Therefore, the study on the improvement of fatigue strength of maraging steel is important. Shot peening is one of effective methods for improving the fatigue strength [4]. However, the increase in surface roughness due to shot peening is very harmful to fatigue strength, because notch sensitivity of high strength steel is very high.

In the present study, rotating bending fatigue tests were carried out for shot-peened maraging steel in order to investigate the effects of shot peening on the fatigue strength and the fracture mechanism focusing on the effect of surface roughness.

2. Material and experimental procedures

The material used was an 18% Ni maraging steel whose chemical

<table>
<thead>
<tr>
<th>Aging condition</th>
<th>Hv</th>
<th>Reversal austenit</th>
<th>σyz</th>
<th>σa</th>
<th>σw</th>
<th>δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>753K-48ks</td>
<td>534</td>
<td>0</td>
<td>2073</td>
<td>2156</td>
<td>600</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Table 2. Shot peening conditions.

<table>
<thead>
<tr>
<th>Blasting equipment</th>
<th>Air type</th>
<th>Material</th>
<th>Size (mm)</th>
<th>Hardness</th>
<th>Specific gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot</td>
<td></td>
<td>Steel</td>
<td>Ø0.6 , Ø1.1</td>
<td>HV=700</td>
<td>7.5</td>
</tr>
<tr>
<td>Cemented carbide</td>
<td></td>
<td>Ø0.05</td>
<td>HV=1400</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Blasting</th>
<th>Single shot</th>
<th>Double shot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (mm)</td>
<td>Ø0.6 , Ø1.1</td>
<td>Ø1.1 , Ø0.05</td>
</tr>
<tr>
<td>Arc height (mm A)</td>
<td>0.430 , 0.730</td>
<td>0.730 , 0.075</td>
</tr>
<tr>
<td>Time (sec)</td>
<td>6 , 6</td>
<td>12 , 6</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>0.3 , 0.3</td>
<td>0.3 , 0.3</td>
</tr>
<tr>
<td>Distance (mm)</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>Coverage (%)</td>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>
composition in weight was 0.005C, 0.05Si, 0.03Mn, 18.7Ni, 5.01Mo, 8.94Co, 0.92Ti, 0.12Al and remainder Fe. The material was solution treated for 5.4 ks at 1123K in vacuum, followed by air cooling and age hardening in a salt bath.

Figure 1 shows the aging curve and the condition used for the fatigue test. As the aging condition for the fatigue test, the under-aging condition of 753K-48ks was selected considering that the material had sufficiently high hardness and high fatigue strength, and that a marked effect of shot peening was confirmed in the preliminary test.

Table 1 shows the mechanical properties.

Figure 2 shows the shape and dimensions of specimen. After machining, all the specimens were electropolished by about 20 μm from the surface layer.

Table 2 shows the shot peening conditions.

Distributions of hardness and residual stress were measured by using a micro Vickers hardness tester and an X ray diffraction device, respectively.
Surface roughness was measured using a stylus-type profilometer and was the average value of five points of maximum roughness \( R_y \). Fatigue tests were carried out using an Ono-type rotating bending fatigue testing machine with a capacity of \( 15 \, \text{N} \cdot \text{m} \) operating at about \( 50 \, \text{Hz} \). Shot peened surface was observed using a scanning electron microscope.

3. Experimental results and discussion

Figure 3 is examples of SEM photographs of shot peened surfaces. Surface roughness was markedly improved by double shot peening.

Figures 4 and 5 show the distributions of hardness and residual stress, respectively. By shot peening, the surface layer was hardened and

(a) Single shot (\( \phi 1.1 \text{mm} \)), \( R_y = 27 \mu \text{m} \)  
(b) Double shot (\( \phi 1.1 \text{mm} + \phi 0.05 \text{mm} \)), \( R_y = 12 \mu \text{m} \)

Figure 3: Shot peened surface.

Figure 4: Hardness distribution.
compressive residual stress was generated. The hardening was high in case of double shot peening, though the distribution of residual stress did not change, except for the one near the surface.

S-N curves of electro-polished specimens and specimens peened by 1.1 mm shot are shown in Fig. 6, in which solid marks and open marks indicate an internal fracture and a surface fracture, respectively, and half solid marks indicate a combined fracture of internal and surface as will be described in detail hereinafter. Fatigue strength is strongly increased by shot peening and the shape of S-N curve of peened specimen is complex.

Figure 7 is an example of a crack initiated at peened surface at high stress level. Cracks initiated at the stress concentrated parts like a rugged or

![Figure 5: Distribution of residual stress.](image)

![Figure 6: S-N curves.](image)
Figure 7: Initiated crack at shot peened surface (φ 1.1 mm).

Figure 8: SEM photographs at several stress levels.

(a) $\sigma_s = 1400$ MPa, $N = 2.3 \times 10^6$ cycles
(b) $\sigma_s = 1100$ MPa, $N = 1.7 \times 10^5$ cycles
(c) $\sigma_s = 750$ MPa, $N = 5.4 \times 10^7$ cycles

Figure 8 is SEM photographs showing the fracture surfaces at several stress levels. Fracture occurred from specimen surface at high stress levels, while an internal fracture occurred at low stress levels. And at the middle stress levels, both fracture modes were observed. In general, fracture made is either the surface or the internal of specimen, consequently S-N curve showed a double-step wise in surface hardened steels [5],[6]. In this case, however, combined fracture existed at middle stress levels. This may be the reason why S-N curve does not show definite step. Moreover, fatigue strength for the surface fracture may be increased by improvement of surface roughness and
distributions of hardness and residual stress. That is, it is effective to smoothen the surface and to maximize the peak of hardness and compressive residual stress near the surface.

Figure 9 shows S-N curves for specimens electro-polished the peened surface by about 100μm. In the figure, the results of double shot peened specimens using super hard fine particles are also shown. Fatigue strengths are markedly improved, in spite of the small decrease in the depth of hardened layer due to electro-polishing. Moreover, the similar effect is obtained by double shot peening. However, the influence of shot peening condition on the fatigue strength in long life region, where the internal fracture occurred, is very small. In the following, the improvement of fatigue strength in long life region will be investigated.

Figure 10 is SEM photographs magnified the crack initiation site and the boundary between the internal crack and the surface crack. A crack initiates from an inclusion and the surface is relatively flat around the inclusion, though a rough granular area is observed near the inclusion. Moreover, many intergranular cracks are observed at the boundary between the internal crack and the surface crack. Murakami et al. [7] investigated the role of hydrogen brittleness in the early growth of fish eye cracks and indicated that a rough surface area can be observed in the vicinity of inclusions which caused internal fractures after a very high fatigue cycles. The formation of rough surface around inclusions was recounted as a result of hydrogen brittleness assisted fatigue crack growth so that crack propagation in this area was extremely slow and discontinuous. On the other hand, authors indicated that the formation of reversion austenite was very

![Figure 9: S-N curves of specimens electro-polished peened surface.](image-url)
Figure 10: SEM photographs of internal crack (without reversion austenite).

Figure 11: S-N curves of steels with and without reversion austenite.

Effective to improve the fatigue strength of maraging steel, especially at low stress levels [8]. Moreover, reversion austenite is insensitive to hydrogen brittleness. These results suggest that the fatigue strength in long life region can be improved by formation of reversion austenite.

Figure 11 is S-N curves showing the influence of the reversion austenite. The results were obtained by using shot size of 0.6mm. In this case, the steel with the reversion austenite was prepared by aging the material at 783°C for 48 ks to obtain the similar static strength (σB=2043 MPa, Hv=627) of the steel without reversion austenite (σB=2065 MPa, Hv=635). Fatigue strength was increased by the formation of reversion austenite in long life region, though the one was decreased by the surface properties of hardness and residual stress in short life region.

Figure 12 shows a SEM photograph of fracture surface for steel with
reversion austenite. A granular facet and intergranular cracks decrease compared with the results of steel without reversion austenite (Fig. 10). Results of Figs. 11 and 12 suggest that the formation of reversion austenite may be effective to improve the fatigue strength through the suppression of hydrogen brittleness.

Figure 13 shows a schematic S-N curve showing the influence of shot peening and the fracture mechanism.

4. Conclusions

Rotating bending fatigue tests were carried out for a shot-peened maraging steel in order to investigate the effects of shot peening on the fatigue strength
and the fracture mechanism focusing on the effect of surface roughness. Main results were summarized as follows:

(1) Fatigue strength was markedly improved by shot peening because of hardening and generation of compressive residual stress in the surface layer.

(2) Origin of fatigue fracture changed from the specimen surface at high stress levels to an inclusion in the interior of specimen at low stress levels. And at the middle stress levels, both fracture modes were observed. Consequently, the shape of S-N curve of shot-peened specimen was complex corresponding to the change of fracture mode.

(3) In the region where surface fracture occurs, polishing the specimen surface and double shot peening using super hard fine particles were effective to improve the fatigue strength through the decrease in stress concentration due to smoothening the specimen surface.

(4) In the region where internal fracture occurs, the formation of reversion austenite was effective to improve the fatigue strength through the suppression of hydrogen brittleness.

References