EFFECT OF RESIDUAL STRESSES ON FATIGUE STRENGTH OF SEVERELY SURFACE DEFORMED STEELS BY SHOT PEENING

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ABSTRACT

The compressive stress distribution below the specimen surface of severely surface deformed steels by shot peening was investigated by using laboratory X-rays and high-energy X-rays from a synchrotron radiation source, SPring-8 in the Japan Synchrotron Radiation Research Institute. Medium carbon steel plates were heat treated in two different conditions. The Vickers hardness of material-A and B after heat treatment is 408 and 617 HV, respectively. The specimens were shot-peened with fine cast iron particles of the size of 50 μm. The coverage was selected to be 5000%. For the synchrotron radiation, by using the monochromatic X-ray beam with several energy levels, the stress values at the arbitrary penetration depth were measured by the constant penetration depth method. The shot-peened specimens were fatigued under four-point bending. The improvement of fatigue strength of material-A was not so large because of large surface roughness. On the other hand, for the material-B, the surface roughness was smaller and the fatigue strength was higher than that of ground specimens.

INTRODUCTION

Life extension of engineering plants and high-speed operation of engineering machines are required in various fields. To obtain long-term reliability of structural materials, sufficient strength against fatigue, fretting fatigue and stress corrosion cracking is required. Since most of material failures occur at surfaces, surface modification is one of the most effective techniques to improve the strength. Shot-peening is widely used to introduce the compressive residual stress at the surface of engineering components [1-3]. In recent years, a new technique of shot-peening has been developed to obtain a nanocrystalline surface layer [4-6]. For the nanocrystalline materials, there are many advantages such as high strength, high hardness and high wear resistance. Techniques such as, equal-channel angular pressing (ECAP) [7], high-pressure torsion (HPT)[8] and accumulative roll bonding (ARB) [9] were developed to obtain nanocrystalline...
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materials in bulk. On the other hand, the nanocrystalline structure only in near surface layer can be easily obtained by surface modification such as shot-peening.

The residual stress at the surface controls the condition of crack initiation. Furthermore, since the stress distribution below the surface is an important factor to determine the condition of crack propagation, estimation of the stress distribution below the surface is required for the design and quality control of components. The X-ray diffraction method is the most powerful nondestructive method to measure the residual stress in crystalline materials. The penetration depth of X-rays, however, is around 10 μm when ordinary characteristic X-rays are used. On the other hand, a synchrotron source produces high-energy X-rays and the penetration depth increases with increasing energy of X-rays.

In the present study, medium carbon steel plates with different hardness were shot-peened. The distribution of residual stress below the surface was measured by using laboratory X-rays and high-energy X-rays from a synchrotron radiation source. Then the fatigue tests under four-point bending were conducted. The effects of hardness, residual stress and roughness on the fatigue strength were investigated.

**EXPERIMENTAL**

The experimental material used is a medium carbon steel with 0.45 mass% carbon content (JIS-S45C). Two kinds of hardness were obtained by heat treatment under different conditions, and were designated by material-A and material-B. Machined specimens were normalized from 1223 K for 1 h. Material-A was oil-quenched from 1123 K for 1 h, and subzero cooling was carried out at the liquid nitrogen temperature. Tempering temperature was 723 K. On the other hand, tempering temperature of material-B was 523 K. The Vickers hardness of material-A and material-B was 400HV and 617HV, respectively. The specimen had a rectangular cross section of 4 x 8 mm² and a length of 76 mm. The specimen surface was finished by a grinding process. The surface of 8 x 76 mm² was shot-peened. The conditions of shot-peening were summarized in Table 1. Shots were made of cast steel, SMB 300, with the hardness of 800HV. The average diameter was 50 μm. The pressure for shot-peening was 0.4 MPa. The distance between the nozzle and the specimen was set to be 200 mm. The coverage was selected to be 5000 % to obtain nanocrystalline surface layer [10].

<table>
<thead>
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<th>Table 1 Conditions of shot peening.</th>
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<td>Shot material</td>
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<td>Partical size (μm)</td>
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<td>Injection pressure (MPa)</td>
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<td>Projector distance (mm)</td>
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<td>Scanning speed (mm/s)</td>
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Figure 1 shows the scanning electron micrograph of the cross section of the specimen. The specimen surface of material-A is rougher than that of material-B, and the average roughness in the longitudinal direction is 3.45 μm and 2.07 μm for material-A and material-B, respectively. In these shot-peening conditions, the nanocrystalline surface layer of about 10 μm is formed [10]. Figure 2 shows the distribution of the micro Vickers hardness measured on the cross sectioned surface of the specimen. The hardness near the surface is more than 1000 HV. The hardness decreases rapidly with increasing depth. When the distance from the surface is larger than about 20 μm, the hardness becomes the value for the matrix.

The stress distribution below the shot-peened surface was first determined by the sin²ψ method using a conventional laboratory X-ray equipment with a rotating anode (Mac Science MXP18).
The Fe 211 diffraction by the characteristic X-ray of Cr-Kα radiation was used for stress measurement. The specimen surface was removed by sequential electropolishing. The conditions of stress measurement were summarized in Table 2. The stress measurement by using high-energy X-rays was conducted at the beamline BL02B1 of SPring-8 (Super Photon ring-8 GeV) in the Japan Synchrotron Radiation Research Institute (JASRI). This beam line yields X-rays with energy levels ranging from 5 and 115 keV and is equipped with a seven-circle goniometer. The constant penetration depth method [11-14] was adopted for the stress measurement by using high-energy X-rays with energy levels from 10 to 72 keV. Several diffraction profiles of single peaks and overlapping peaks were used for stress measurement. Measured diffraction profiles were analyzed as a single peak by using Lorentzian function. The penetration depth was set to be from 0.5 μm to 250 μm, and was calculated by Eq.1 [11, 12].

\[
\tau = \frac{\cos \chi \sin \omega}{\mu} \frac{\sin(2\theta_0 - \omega)}{\sin \omega + \sin(2\theta_0 - \omega)}
\]  

(1)

where \( \theta_0 \) is the diffraction angle from stress-free materials, \( \mu \) is the linear absorption coefficient. The values of \( \omega \) and \( \chi \) are angles of inclination between the incident X-rays and the specimen surface. The angle between the normals of diffraction plane and the specimen surface, \( \psi \), is given by Eq.2.

\[
\cos \psi = \cos \chi \cos(\theta_0 - \omega)
\]

(2)

The elastic constants for each diffraction plane were calculated by Kroener's model [15].

Fatigue tests were conducted in a servo-hydraulic fatigue testing machine under four-point bending for both materials. The outer span was 60 mm and the inner span was 20 mm. Frequency was between 20 and 30 Hz. The stress ratio was 0.1.

RESULTS AND DISCUSSION

The stress distribution determined by the conventional \( \sin^2 \psi \) method using laboratory Cr-Kα radiation is shown in Fig. 3. The specimen surface was removed by sequential electropolishing. Figure 3 (a) shows the data obtained for material-A. In the figure, the solid marks indicate the corrected value for the stress relief due to surface removal [16]. The residual stress near the specimen surface is -684 MPa. The compressive residual stress decreases rapidly with depth from the surface. Especially, the slope within 10 μm is very steep. The depth of the compressive stress region is about 150 μm. On the other hand, the stress near the surface of material-B is -1240 MPa.
as shown in Fig. 3 (b). The value is almost twice that of material-A. The compressive stress extended about 200 μm below the surface.

The surface removal method using laboratory X-rays was often adopted to determine the stress distribution below the specimen surface, however that is not a nondestructive method. By using high-energy X-rays from a synchrotron radiation source, distribution of the residual stress below the specimen surface can be estimated nondestructively. The measured stresses using synchrotron X-rays are summarized in Fig. 4. In the figures, the solid line indicates the weighted average.
stress, \( \langle \sigma \rangle \), calculated from the residual stress measured by laboratory X-rays as shown in Fig. 3.

\[
\langle \sigma \rangle = \frac{\int_0^h \sigma(z) e^{-z/H} \, dz}{\int_0^h e^{-z/H} \, dz}
\]  

(3)

where \( z \) is the depth from the surface, \( \sigma(z) \) is the measured stress by laboratory X-rays, \( h \) is the thickness of the specimen, and \( H \) is the penetration depth. Measured stresses agree very well with the solid line. Once the weighted average stress is measured as a function of the penetration depth, the stress distribution in real space can be predicted by an optimization approach. The stress distribution is assumed by two polynomials. The coefficients of the polynomials are determined on the basis of the minimization of the error sum of squares between calculated and measured stress. The predicted residual stress distribution was indicated in Fig. 3(a) for material-A [12].

Figure 5 shows the typical examples of diffraction profile measured by synchrotron X-rays. In the figure, the open marks and the solid marks indicate the data obtained at the penetration depth of 4 \( \mu \text{m} \) and 21 \( \mu \text{m} \), respectively. For both materials, the value of FWHM at 4 \( \mu \text{m} \) is larger than that at 21 \( \mu \text{m} \). The crystallite size and the microstrain calculated from the diffraction profiles are plotted in Fig. 6 [17]. The crystallite size of material-A is larger than that of material-B. The value increases with increasing penetration depth for both materials.

Fatigue strength was investigated under four-point bending. Figure 7 shows the S-N data for both materials. In the figure, the solid marks and the open marks indicate the data obtained for shot-peened specimens and ground specimens before shot-peening, respectively. For material-B,
improvement of fatigue strength by shot-peening is about 50 MPa. On the other hand, fatigue strength of shot-peened specimens and ground specimens is almost the same for material-A. For the case of material-A, fatigue cracks initiated at the concave portion on the shot-peened surface. As described before, the surface roughness of material-A is relatively large. In general, fatigue strength of harder materials is very sensitive to defects. Then the surface roughness acts as a defect for fatigue loading. On the other hand, for material-B, the crack initiation site was a corner or interior of the specimen. The roughness is also important as well as the hardness and the residual stress to improve the fatigue strength.

CONCLUSIONS

Residual stress distribution below the specimen surface of severely surface deformed medium carbon steels by shot-peening was measured by X-ray method. Then the shot-peened specimens were fatigued under four-point bending. The principal results are summarized as follows:
1. The Vickers hardness on the shot-peened surface was almost the same for both materials. The hardness decreases with depth from the surface. When the depth is larger than about 20 µm, the hardness becomes the value for the matrix.
2. The residual stress on the surface was -684 and -1240 MPa in Material-A and material-B, respectively. The depth where the residual stress becomes zero was slightly deeper in material-B.
3. The distribution of the residual stress measured by the constant penetration depth method using synchrotron X-rays agreed very well with the weighted average stress calculated from the data.
measured by laboratory X-rays. The crystallite size in material-A is larger than that in material-B. The value increases with penetration depth for both materials.

4. The roughness is important as well as the hardness and the residual stress to improve the fatigue strength.

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REFERENCES