Compressive residual stress relaxation behavior of shot peened AISI4140 steel during first cycle of repeated loading

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Abstract

This study aims to reveal the relaxation behavior of the compressive residual stress induced by shot peening during the first cycle of cyclic loading. An hourglass-type specimen was machined from AISI440 steel, and the surface was shot peened using high-speed steel. The relaxation behavior of the compressive residual stress was investigated using an *in-situ* X-ray stress measurement method. Results shows that the compressive residual stress relaxation occurred during the compression process of the first fatigue loading, and the relaxation occurred continuously after the first cycle.

Keywords Residual stress, Relaxation, in-situ X-ray measurement, fatigue.

Introduction

Shot peening is an effective method to improve the fatigue properties of steel. Compressive residual stress is one of the important factor~~s~~ affecting the fatigue properties of shot peened material as it prevents crack initiation and its propagation [1, 2]. However, the compressive residual stress is relaxed during the fatigue process [2–6] and reducing the benefit in improving fatigue properties. It is important to reveal the relaxation behavior of compressive residual stress to evaluate its effect on fatigue properties. It was reported that the relaxation of the compressive residual stress occurs primarily within the first cycle of fatigue [4–6]. However, the behavior of residual stress relaxation during the first cycle of repeated loading has not yet been clarified. Therefore, this study aims to examine the relaxation behavior of residual stress generated by shot peening during a cycle of repeated loading, using an in-situ X-ray stress measurement [6].

Experimental Methods

The material used in this study was the quenched-and-tempered AISI4140 steel with chemical composition (in wt%): 0.42C, 1.03Cr, 0.16Mo, 0.20Si, 0.75Mn, 0.016P, 0.013S, 0.12Cu, 0.05Ni, 0.0008O and balance Fe. The mechanical properties of AISI4140 steel are listed in Table 1. The material was machined into an hourglass-type fatigue test specimen with the smallest diameter of 5 mm and notch curvature of 24 mm. The smallest diameter section was polished using #100, #320 and #600 emery paper.

Shot peening was performed to generate the compressive residual stress for the smallest diameter section of the specimen. The peening conditions are listed in Table 2. The specimen was rotated on the latch during peening.

Table 1. Mechanical properties of AISI4140 steel

0.2 % proof stress	Tensile strength	Reduction in area	Vickers hardness (9.8 N)
1044 MPa	1133 MPa	54.8 %	335 HV

Table 2. Shot peening conditions.

Particle	High-speed tool steel (700 HV)
Particle diameter	125~150 μm
Projection method	Air blasting
Air pressure	0.6 MPa
Peening time	30 s

Hardness-depth profiles were obtained in cross section using a Vickers hardness tester at a load of 0.98 N. Residual stress was measured using portable X-ray diffraction stress tester. Measurements were performed in the longitudinal direction of the specimen and the stress value was calculated using the cosα method.

Fatigue tests were performed using the electrohydraulic-servo fatigue testing machine under axial loading with a stress ratio of −1 and test frequency of 20 Hz. The test was terminated when the specimen did not fail with a fatigue life of 10^7 cycles.

To investigate the change behavior of compressive residual stress during the fatigue process, *in-situ* X-ray stress measurement [6] was applied. A specimen was fixed to an axial loading fatigue test machine. The stress on the surface, i.e., the sum of applied stress and residual stress, was directly measured through X-ray diffraction without removing the specimen from the test machine. The applied stress was changed stepwise with a stress ratio R = −1, and the stress on the surface of the specimen were measured successively. The applied stress was maintained during the X-ray irradiation.

Experimental Results and Discussion

Fig. 1 shows the distribution of the Vickers hardness of the peened specimen; no increase in hardness was observed on the surface of the specimen owing to peening. The distribution of residual stress on the peened specimen is shown in Fig. 2; approximately 500 MPa compressive residual stress was generated on the peened AISI440 surface, and the total depth of the compressive residual stress region was approximately 90 μm.

The S-N diagram of the shot peened specimen obtained from the fatigue tests with axial loading is shown in Fig. 3; the fatigue life tended to increase as the stress amplitude decreased, and the specimens did not fail at stress amplitude of 500 MPa. The plots with '+' symbol represent the result of the interrupted fatigue test for residual stress measurement, and the ones with the '→' symbol represent the specimens, which did not fail until 10^7 cycles.

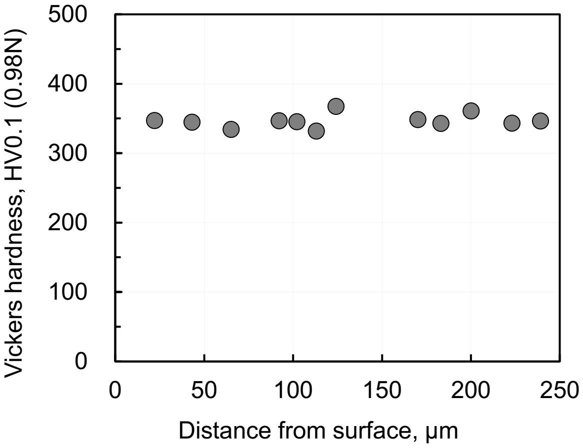

Fig. 1 In-depth Vickers hardness distributions of the peened surface

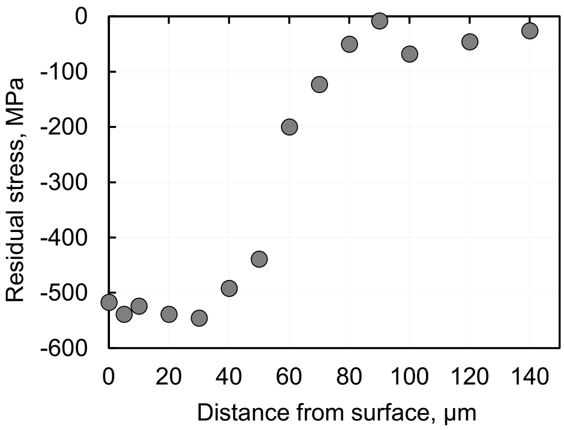

Fig. 2 Distribution of residual stress on the peened surface

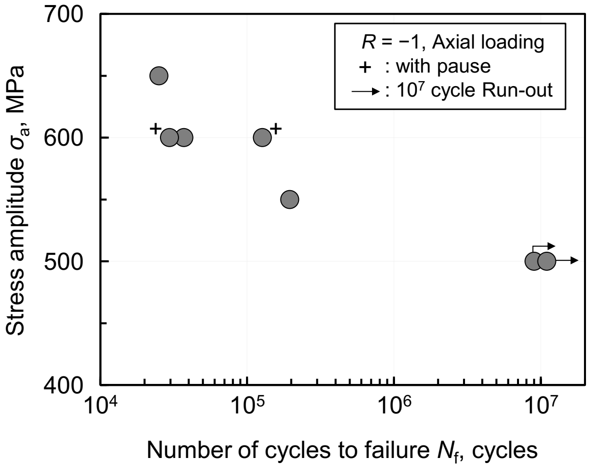

Fig. 3 S-N diagram of the peened AISI440 steel

Fig. 4 shows the surface residual stress of the specimen before and after the fatigue test at stress amplitude of 500 MPa. Before the fatigue test, approximately −500 MPa residual stress existed on the surface of the specimen. However, approximately −300 MPa residual stress remained after the fatigue test as the compressive residual stress was relaxed during the fatigue process.

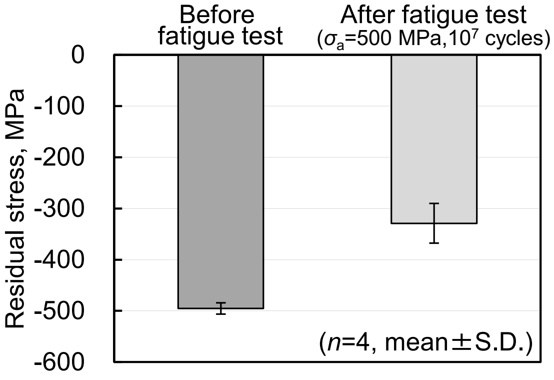

Fig. 4 Surface residual stress of the peened specimen before and after the fatigue test at stress amplitude of 500 MPa

To investigate the relaxation behavior of the compressive residual stress during the on-cycle of fatigue loading, in-situ X-ray stress measurement was applied. Figs. 5(a)~(c) show the relations between the applied stress and surface stress of the specimen during the fatigue test at stress amplitude of 600 MPa. The horizontal axis of the figure represents the applied stress, and vertical axis represents the surface stress measured through X-ray. Fig. 5(a) shows the results for the first cycle. The initial residual stress was approximately −450 MPa. The surface stress decreased linearly with the increase in the compressive applied stress until the applied stress reached approximately −300 MPa. The result indicates that the compressive residual stress did not change. However, non-linear relation between the applied stress and surface stress was observed to determine if the compressive applied stress exceeded −300 MPa. The result indicates that the compressive residual stress was relaxed during the compressive loading. This is owing to local yielding of the compressive residual stress layer. When the compressive stress was unloaded and tensile stress was applied, the surface stress varied linearly with the applied stress. Therefore, these results indicate that the compressive stress loading process is a significant phase in the compressive residual stress relaxation.

Figs. 5(b) and (c) show the results for the second and tenth cycles, respectively. In the second cycle, a nonlinear relationship, i.e., slight release of compressive residual stress can be observed in the compressive loading process. This result indicates that cyclic deformation occurred on the surface compressive layer. In the tenth cycle, relations between the applied stress and surface stress are linear, which indicate low relaxation of compressive residual stress.

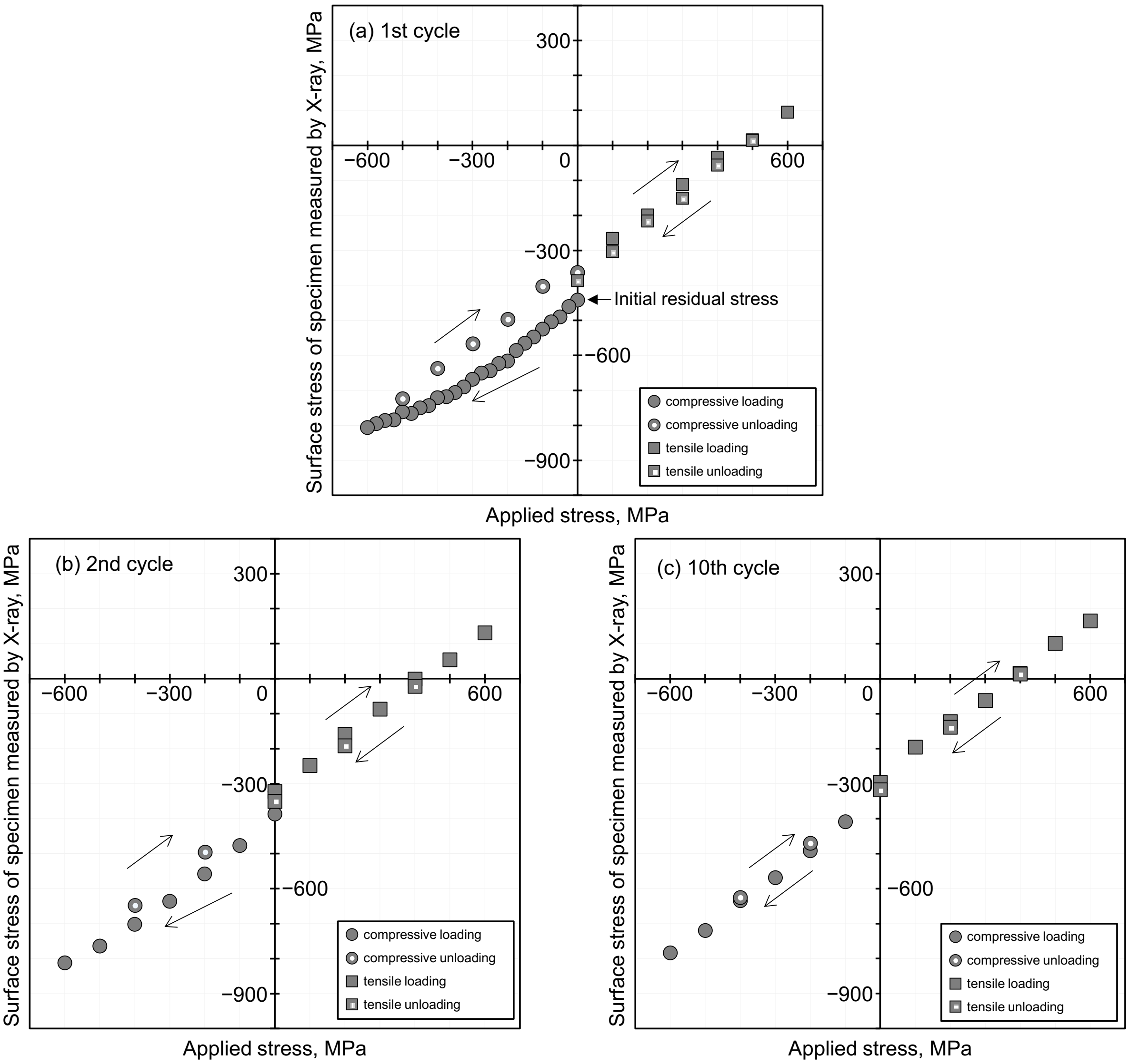

Fig. 5 Relations between the applied stress and surface stress during one cycle of fatigue loading at stress amplitude of 600 MPa; (a) first cycle, (b) second cycle, (c) tenth cycle

The relations between the number of loading cycles and residual stress are shown in Fig. 6. It can be seen that the compressive residual stress, which was initially approximately−450 MPa, was relaxed to approximately −400 MPa during the first cycle. The compressive residual stress was continuously relaxed after the first cycle; however, the amount of release per cycle was found to be decreasing. This is because the cyclic deformation of the surface compressive residual stress layer decreases as the number of cycles increases, as show in Fig. 5.

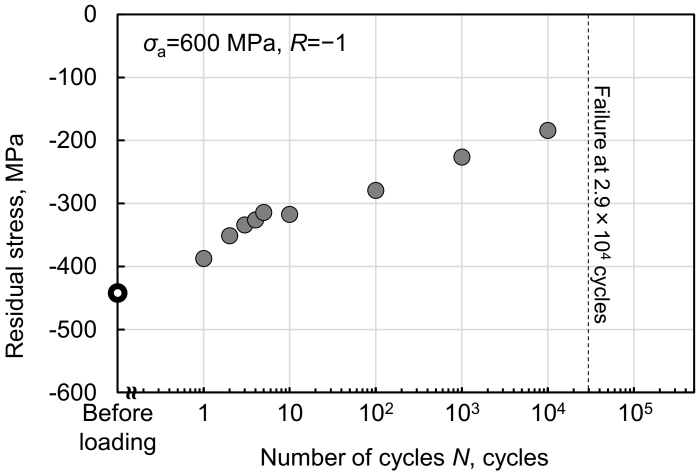

Fig. 6 Change in the residual stress during the fatigue test (stress amplitude = 600 MPa)

Conclusions

In this study, the relaxation behavior of shot peening induced compressive residual stress during a cycle of fatigue loading was investigated using *in-situ* X-ray stress measurement. The following conclusions were drawn:

- Compressive residual stress induced by shot peening is relaxed by the compressive stress in the first cycle of repeated loading. This is owing to the compressive yield of the residual stress layer.
- After the first cycle of loading, the compressive residual is gradually released. The cause of relaxation after the initial cycle is considered to be the cyclic deformation of the compressive residual stress layer.

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