Investigation of Fatigue Crack Growth Behavior on the Shot Peened Carbon Steel by Residual Stress Relaxation

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Abstract
The objective of this study was to investigate the fatigue crack growth behavior on the shot peened (SP) carbon steel during the fatigue test. In general, the compressive residual stress (CRS) induced by SP is the most influential parameter that determines the fatigue strength of SP materials. However, there is some argument that the induced CRS can be relaxed by thermal or mechanical loadings, therefore stability of CRS during cyclic loads is a great important aspect for SP process. In this regard, it is necessary to understand their influence on the fatigue crack formations, quantitatively. In this study, the evaluations of fatigue crack growth during the fatigue life associated with residual stress relaxations on the properties of a material were considered. To this end, rotating bending fatigue tests were carried out to introduce the mechanical loadings, and quantitative measurements of the residual stress were made by X-ray diffraction (XRD) technique, and the plastic replication technique was chosen for the crack growth analysis. This presentation discussed the fatigue crack growth behavior by redistributions of induced CRS in detail.

Keywords Shot peening, residual stress relaxation, crack growth behavior, carbon steel

Introduction
The influence of SP on fatigue strength have been studied for many years. In order to develop the SP techniques with the new engineering structural materials and operating environments. Basically, the fatigue strength of SP material is determined by parameters as following: (i) surface roughening, (ii) work hardening, and (iii) CRS layer. Of these, the CRS is the most crucial parameter for improvement of the fatigue strength [1]. However, there are some indications that the induced CRS can be relaxed by thermal or mechanical loadings [2-4]. In addition, the previous works [5, 6] showed that as the applied stress amplitude increased, the beneficial effects of SP decreased because of residual stress relaxation during the fatigue life. Therefore, this residual stress relaxation is the most important aspect of SP process. Hence, their stability during mechanical cyclic loadings is of great importance in the design of components that will be subjected to actual service loading conditions. The authors previously found as following [5-7]: (i) surface microcracks occurred during the peening treatment, which was unavoidable consequence of the peening process, and (ii) degradation of induced CRS was found under the relaxation rates for residual stress dependent on the applied stress amplitudes. Besides, it was found that the critical condition of the threshold-residual stress relaxation boundary that had a significant influence on the fatigue strength. From the fundamental previous results, we suggested that the fatigue life of SP material was strongly controlled by residual stress state and fatigue failure occurred when the induced CRS relaxed below the critical threshold boundary, as shown in Figure 1. The objectives of this study were to evaluate the fatigue crack growth behavior of SP carbon steel during the fatigue life associated with residual stress relaxations for the actual relation between the threshold condition and fatigue crack formation. To this end, the conventional SP condition was selected for this testing. Focused ion beam (FIB) milling was used to introduce small notches as equivalent crack size of existed crack length into the smooth specimens; here, the surface re-polishing (RP) was successfully carried out after SP treatment. Detailed process will be discussed by next section.

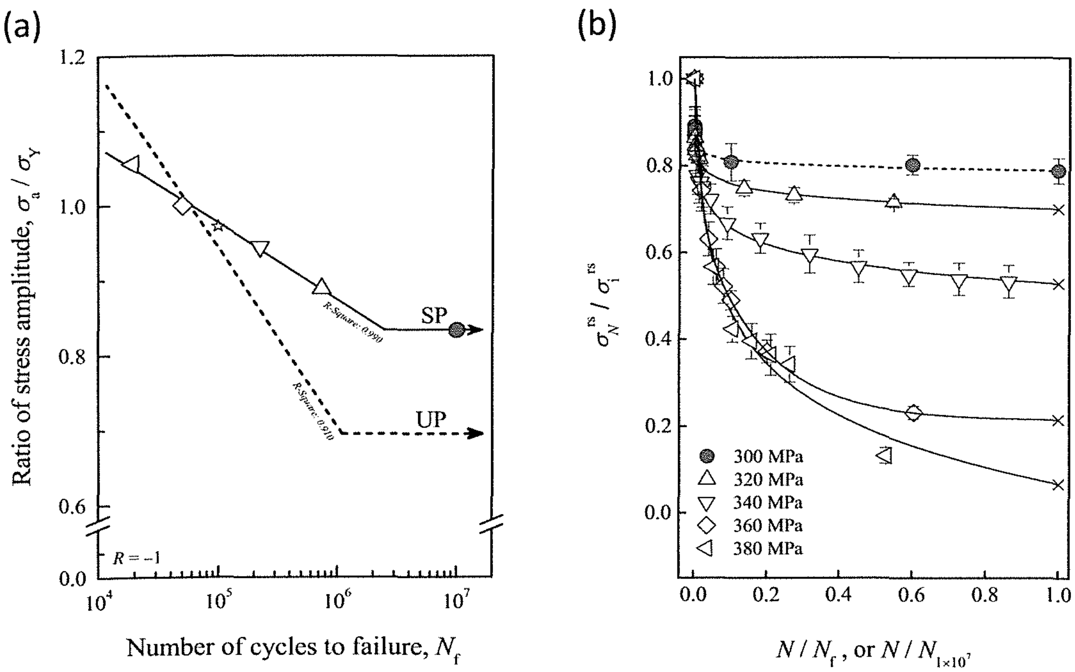

Figure 1. (a) S–N curves of the shot-peened and un-peened conditions [6], (b) Relative surface residual stress redistributions during mechanical loads [7].

Experimental Methods

The material used in this study was an annealed medium carbon steel (JIS-S45C). The chemical composition of the samples is presented below. C-0.46, Si-0.20, Mn-0.73, P-0.029, S-0.017, Al-0.018, and Fe-Balance (in wt.%), and the mechanical properties of this steel are: yield strength of 360 MPa, tensile strength of 633 MPa, fatigue limit of 250 MPa and 175-185 Hv. These properties were obtained by means of solution heat treated at 845°C for 1 hour and subsequently in furnace cooling. Figure 2a shows the shape of the rotating–bending fatigue specimens along with their dimensions. All the specimens were polished with grade 2000 paper and a buffing pad in order to remove machining marks. After completion of the final specimen preparation, the central part of each specimen was subjected to SP under at intensity of 0.36 mmA [8]. The residual stress was measured using a standard X-ray diffraction technique carried out with X-ray equipment (PSPC-RSF/KM, Rigaku Corp.). The measurements [6] were carried out at the beginning and after each predefined number of cycles in the longitudinal direction at the center of positions by the conventional $\sin^2\Psi$ method. The Cr Kα X-rays were used with a V-filter, and the diffraction plane was (211). The X-ray tube voltage of 30 kV, tube current of 40 mA, and observations at 2θ = 156.4° were undertaken. In addition, ten Ψ angles (0.0°, 13.6°,19.5°, 24.1°, 28.1°, 31.8°, 35.3°, 38.6°, 41.8°, and 45°) were selected to calculate the residual stress and the measurement conditions were determined using general recommendations for radius-convex specimen shapes [9]. The rotating–bending fatigue tests were performed with a stress ratio of R = −1 at room temperature, using a frequency of about 60 Hz. In order to observe the fatigue crack formation the plastic replication technique was chosen for the crack growth analysis with four initial small notches, as shown in Figure 2b. Briefly, FIB milling (Quanta 3D 200i, FEI Corp.) was used to introduce small notches after surface RP, as equivalent crack size of existed crack; the size of the FIB notch was chosen according to the maximum CRS layer and initial length of micro-damages [7]. The FIB was set to a voltage of 30 kV and a current of 30 nA was used with rectangular shape, as shown in Figure 2b.

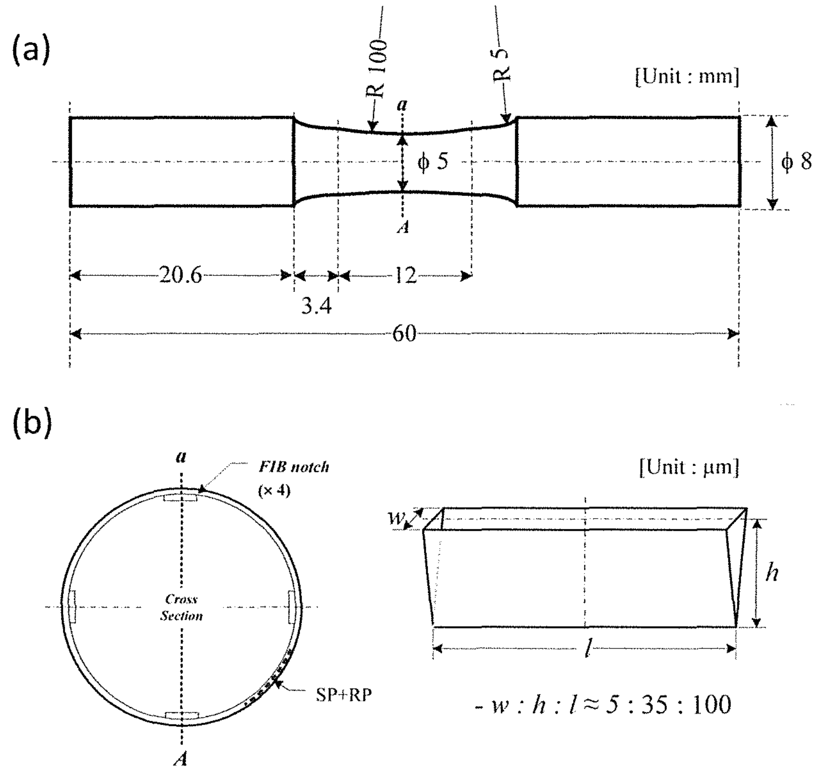

Figure 2. (a) Shape of rotating bending fatigue specimens with dimension, (b) The positions and placement of the FIB notches with specific size.

Experimental Results

As reminder, the authors previous works [5-7] showed that (i) the critical surface damages occurred during the SP process; it caused the fatigue life degradations when the applied stress amplitude exceeded the yield strength of the original material, and (ii) the induced CRS decreased during the fatigue test; it can be explained in terms of stress relaxation, as shown in Figures 1. (a) and (b), respectively. Besides, these relaxations have a critical threshold boundary, which can be used to determine the fatigue strength of SP materials. Figures 3. (a), (b) and (c), (d) shows the relative residual stress redistributions and fatigue crack growth during the fatigue test, respectively. From the results, it should note that relaxation rate of initial induced CRS was much higher when the applied stress amplitude condition was at the yield strength of original material. It may understand that stress relaxations have strongly relative with additional micro- or macro levels of plastic deformations during the fatigue life. Moreover, as the authors already suggested the critical threshold relaxation boundary, when the induced CRS is below at around 80% the fatigue crack could be initiated or propagated until failure occurred. In this regard, the present our results show in good agreement to the critical threshold boundary principle. From the crack growth plots, as show in Figures 3. (c) and (d), it is possible to observe that there is a clear level of the induced CRS at around 74%, where the fatigue crack propagation can be expected regardless of different applied stress amplitudes. The micrographs images of the fatigue crack formations from the FIB notch are shown in Figure 4. As resulted above, it is significant to note that the fatigue life on the SP materials as like a crack formations, was determined by induced CRS state. In addition, it seems that induced CRS delay the crack growth and it is definitely stress dominant phenomenon during the fatigue life. Therefore, it is possible to evaluate the fatigue damage according to the residual stress redistributions. It will be discussed in a subsequent paper.

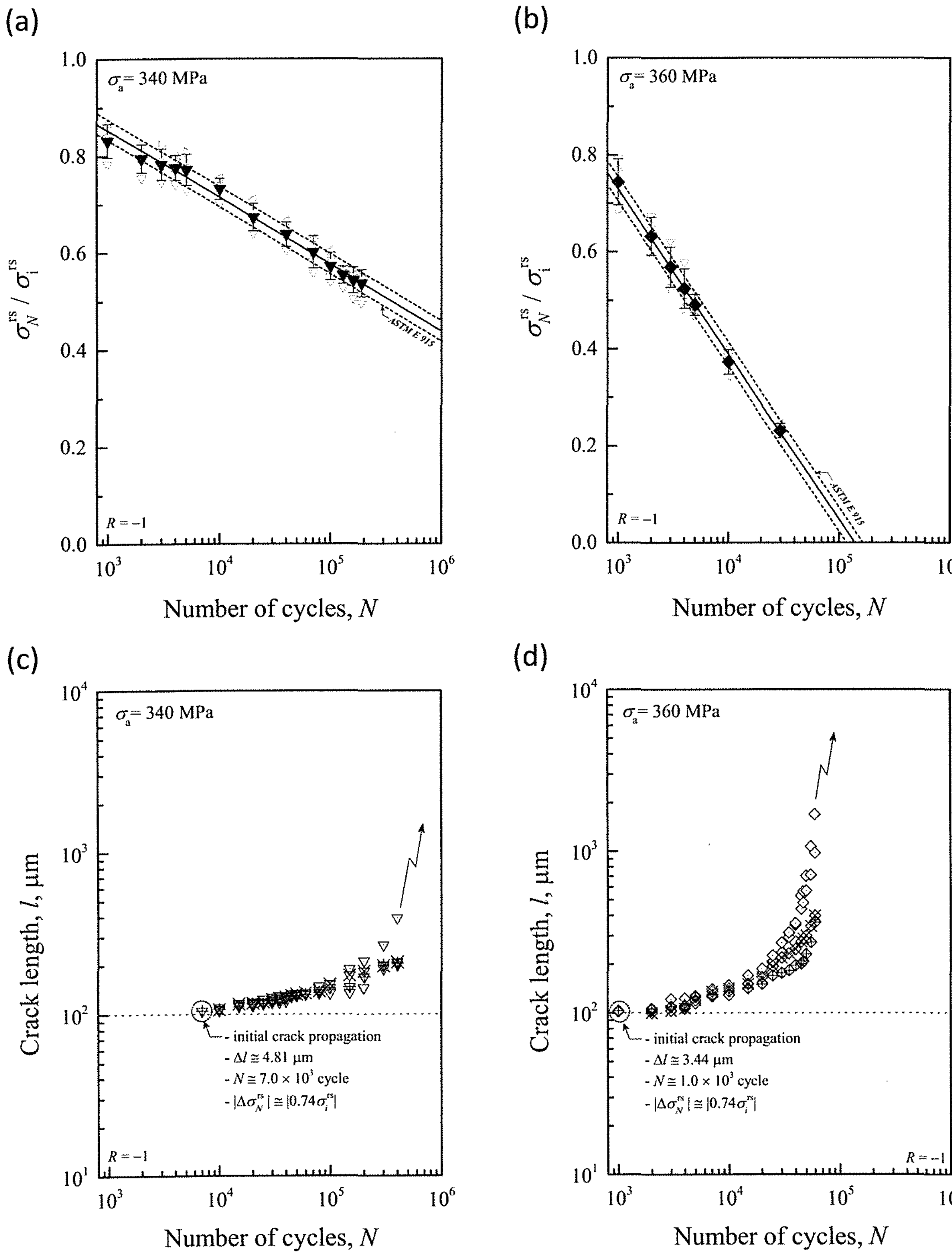

Figure 3. Relative surface residual stress redistributions during mechanical loads [7]: (a) and (b). Growth of fatigue cracks from 100 micron sized FIB notches: (c) and (d). Applied stress amplitudes at 340 MPa and 360 MPa, respectively.

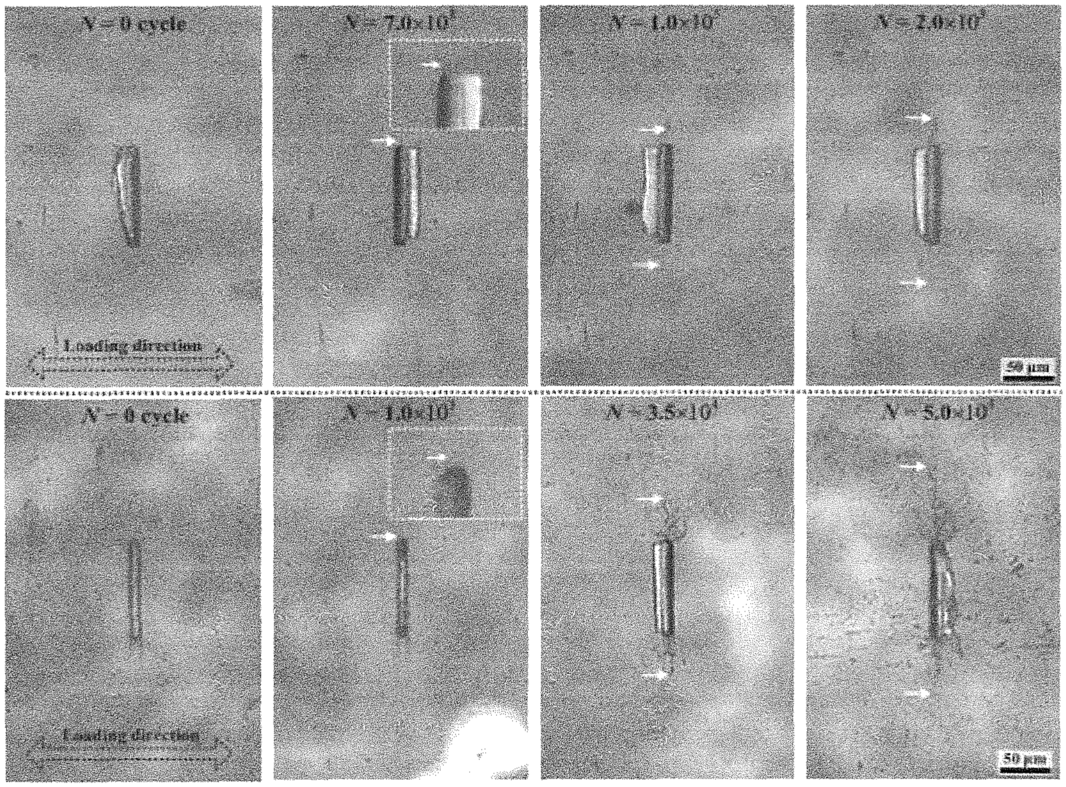

Figure 4. Optical micrographs of the fatigue cracks for specimen with 100 micron sized FIB milled notch by replica technique: (a) applied stress amplitude at 340 MPa and (b) applied stress amplitude at 360 MPa. Arrows indicate position of crack tip.

Conclusions

The present study investigated the fatigue crack growth behavior on the shot-peened medium carbon steel according to the residual stress redistributions. The results obtained based on measurements of the surface plastic replication technique with FIB milled notches can be concluded as follows:

(1) The initial CRSs were relaxed as the number of cycles increased, moreover when the applied stress amplitude exceeded the yield strength of original material, it caused the much higher rate of stress relaxations.

(2) The initial fatigue crack formations at the FIB notches were observed below the critical threshold relaxation boundary which were suggested by previous works.

(3) Moreover, the initial crack formations were observed at around 74% from the initial induced CRS regardless of difference applied stress amplitudes.

(4) It can be assumed that the fatigue behavior of SP materials is stress dominant processes.

References

[1] Gray H, Wagner L, Lütjering G, *Influence of shot peening induced surface roughness, residual macro stresses and dislocation density on the elevated temperature HCF-properties of Ti alloys*, In: Proc. 3rd International Conference on Shot Peening (ICSP-3), Germany; 1987. pp 447-458.

[2] Torres MAS, Voorwald HJC, *An evaluation of shot peening, residual stress and stress relaxation on the fatigue life of AISI 4340 steel*, International Journal of Fatigue, Vol. 24 (2002), pp 877-886.

[3] Dalaei K, Karlsson B, Svensson LE, *Stability of shot peening induced residual stresses and their influence on fatigue lifetime*, Material Science and Engineering (A), Vol. 528 (2011), pp 1008-1015.

[4] John R, Buchanan DJ, Caton MJ, Jha SK, *Stability of shot peen residual stresses in IN100 subjected to creep and fatigue loading*, Procedia Engineering, Vol. 2 (2010), pp 1887-1893.

[5] Kim JC, Cheong SK, Noguchi H, *Evolution of residual stress redistribution associated with localized surface microcracking in shot-peened medium-carbon steel during fatigue test*, International Journal of Fatigue, Vol. 55 (2013), pp 147-157.
[6] Kim JC, Cheong SK, Noguchi H, *Residual stress relaxation and low- and high-cycle fatigue behavior of shot-peened medium-carbon steel*, International Journal of Fatigue, Vol. 56 (2013), pp 114-122.
[7] Kim JC, Cheong SK, Noguchi H, *A non-microstructural crack formation model for understanding fatigue life degradation in shot peened carbon steel under LCF loading*, International Journal of Fatigue, Vol. 63 (2014), pp 110–117.
[8] MIL-S-13165C. *Military specification: shot peening of metal parts*; 1989.
[9] Hilley ME, *Residual stress measurement by X-ray diffraction*, SAE J748a, 2003ed.