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Proposed fatigue damage measurement parameter for shot-peened carbon steel based on fatigue crack growth behavior

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ABSTRACT

A new technique for evaluating fatigue-damage accumulation in shot-peened (SP) carbon steel based on variations in residual stress is proposed. Using findings from previous studies, a fatigue damage parameter for a material treated with SP based on the change in induced compressive residual stress (CRS) is examined. A plastic replica method with the focused ion beam (FIB) technique is used to assess the relationship between the residual stress state and the fatigue crack growth (FCG) behavior of SP specimens over the fatigue lifespan. It is found that the residual stress relaxation phenomenon can be used as an effective parameter for determining the fatigue damage growth, provided the residual stress relaxation rate of each mechanical load and the critical threshold relaxation boundary of each material is known.

1. Introduction

Fatigue damage problems experienced by engineered structures and their effects on reliability during the service period are important issues in a number of industries. Therefore, many attempts have been made to improve fatigue lifespan [1–4] and to quantify damage growth [5–8] in these situations. In terms of fatigue lifespan extension, shot-peening (SP) is an effective tool with regards to the induced compressive residual stress (CRS) near the surface, and has strongly retarded fatigue crack growth under cyclic loads [9,10]. However, the beneficial effects of SP can decrease or disappear as a result of the residual stress relaxation phenomenon during the fatigue lifetime [3,11]. The authors' previous work [12] has involved a qualitative analysis of residual stress relaxation in SP carbon steel over the fatigue lifespan. From the results, we have found that the critical factors of the relaxation process are as follows: (i) the relaxation of residual stresses is dependent on the applied stress amplitude and number of cycles, and its linearly proportional decrease is based on the logarithm of the number of cycles, and (ii) the CRS has a critical relaxation boundary as, when the induced CRS remains at approximately 80% (in the case of carbon steel), failure does not occur. However, when the induced CRS is relaxed below the abovementioned critical condition, fatigue cracks can be initiated or propagated until failure occurs. From these previous results, it can be assumed that changes in the induced CRS during the fatigue lifespan could be an effective parameter for determining the level of sustained fatigue damage, and even the optimal conditions for SP components.

Briefly, fatigue damage is the accumulation of microstructural changes under mechanical loads (plastic deformation) such as dislocation motion [13,14], which can lead to the fracturing of engineering components. The fatigue fracture mechanism, which occurs even under applied stress amplitudes below the yield strength of the original material, may be explained as being the result of accumulation. Therefore, in order to increase the fatigue lifespan and the reliability of engineering structures, it is necessary to understand the damage accumulation process. However, there is no direct method of measuring fatigue damage as a result of unknown factors [14]. For damage evaluation, we should define a damage parameter which can be clearly associated with damage growth. To date, various damage parameters (elastic, electric, acoustic, magnetic properties, etc.) have already been suggested by other researchers to quantify damage growth in their applications [5–7]. However, they are still difficult to detect and the damage growth is not clearly quantifiable. Moreover, it is also important to define the damage parameter as being associated with a specific type of damage source, and even a maximum damage limit. In this regard, a clearer method or parameter for evaluating fatigue damage growth is required.

Some studies on conducting fatigue strength evaluation and fatigue damage analysis of SP materials have already been published. Bagherifard et al. [15,16] proposed that fatigue strength criteria on SP notched specimens based on (i) fracture mechanics

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Nomenclature

SP	shot-peened or shot-peening	N_f	number of cycles to failure
UP	un-peened	σ_i^{rs}	initial residual stress value
CRS	compressive residual stress	σ_N^{rs}	residual stress value after N cycles
FIB	focused ion beam	$\Delta\sigma^{rs}$	redistribution of surface residual stress
RP	re-polishing	σ_a	applied stress amplitude
FCG	fatigue crack growth	σ_Y	yield strength of original material
mmA	peening intensity (by Almen A test strip)	$2a$	crack length
XRD	X-ray diffraction	da/dN	crack propagation rate
ψ	tilting angle	β	damage growth parameter
R	stress ratio		
N	number of cycles		

concepts and (ii) local stress approaches. In particular, Pariente and Guagliano [17] have suggested an experimental technique to analyze contact fatigue damage to SP gears by means of X-ray measurements. However, residual stress relaxation was not considered in these results, and a systematic study of the influence of residual stress on fatigue behavior has not been conducted, especially in regards to physical fatigue crack formation.

Returning to the main topic of this study, the induced CRS by SP decreases drastically as a result of residual stress relaxation during the fatigue lifespan [12]. In this regard, the change in induced CRS over the fatigue lifespan can be an effective parameter for achieving fatigue-damage quantification.

The objectives of this study are to use residual stress changes during fatigue life to evaluate fatigue damage growth in terms of stress relaxation in SP carbon steel. To this end, during the fatigue tests, surface residual stress is measured using X-ray diffraction (XRD), and the plastic replica method with the focused ion beam (FIB) technique is adopted in order to analyze the actual relationship between the residual stress state and fatigue crack growth behavior over the fatigue lifespan. This study discusses fatigue crack formation in relation to CRS level in detail, and proposes a method of evaluating fatigue damage in SP carbon steel using the residual stress state.

2. Experimental procedure

Annealed medium carbon steel, which is the typical material used in industrial fields, was used for the characterization of the induced CRS relaxation and the fatigue crack growth (FCG) behavior. The specimens were machined from a round bar after solution treatment for 1 h at 845 °C, followed by cooling. The chemical composition of the samples was: C – 0.46, Si – 0.20, Mn – 0.73, P – 0.029, S – 0.017, Al – 0.018, and Fe-balance (in wt.%). The sample exhibited a yield strength of 360 MPa, tensile strength of 633 MPa, and Vickers hardness of 175–185 Hv. Fig. 1 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 stage, the central part of each specimen was subjected to SP under a 0.36-mmA intensity with full coverage using a centrifugal wheel-type peening machine [18]. In particular, cut wire shots were used in the peening treatment, with a diameter of 0.8 mm, and the detailed peening conditions are described in Ref. [10].

The residual stress was measured using a standard X-ray diffraction technique conducted using PSPC–RSF/KM X-ray equipment (Rigaku Corporation, Japan). The measurements were conducted at the beginning and after each set of a predefined number of cycles, in the longitudinal direction at the center of the pre-marked positions and using the conventional $\sin^2\psi$ method [19], as shown in Fig. 1a. Here, the transverse stress was not considered in the present research because the residual stress in the longitudinal direction controlled the fatigue crack propagation and the most significant stress was relaxed in the loading direction (longitudinal direction) [20,21]. Cr Kα X-rays were used (with a V-filter), and the diffraction plane was (2 1 1). An X-ray tube voltage of 30 kV, tube current of 40 mA, and incident slit of 2 mm were used and observations at $2\theta = 156.4°$ were made. However, although the incident X-rays are strongly absorbed by the metal, the X-ray penetration depth is only approximately 10 μm from the surface, which is a relatively short distance [19,22,23]. 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 [19]. The subsurfaces were measured after successive layer removal by electrolytic polishing (using 2000 mL of phosphoric acid with a concentration of 85%, 40 g of gelatin, and 40 g of oxalic acid dehydrate), and the results are shown in Fig. 2a. These measurements were completed without stress correction [24], because this study was focused on surface residual stress distribution.

In order to observe fatigue crack formation according to residual stress state, the plastic replica technique was chosen for the crack growth analysis with an initial FIB-ed notch, as shown in Fig. 1b. Briefly, the replica technique is a method for crack detection, and it is a nondestructive evaluation (NDE) of structural materials or components. The detailed method and procedure are described in the Standard Practice for Production and Evaluation of Field Metallographic Replicas ASTM E 1351 [25]. FIB milling (Quanta 3D 200i, FEI Corp.) was used to introduce a small notch after surface re-polishing (RP), equivalent to the crack size of the existing crack in the SP specimen. The size of the FIB-ed notch was chosen to be smaller than the maximum CRS depth and similar to the initial micro-damage length, as shown in Fig. 2a [10]. The FIB was set to a voltage of 30 kV and a current of 30 nA was used with a rectangular shape, as shown in Fig. 2c.

The rotating–bending fatigue tests were performed with a stress ratio of $R = -1$ at room temperature, using a frequency of approximately 60 Hz. The fatigue test was stopped at the predefined loading cycle: the intervals were increased exponentially, after which the surface was characterized using the plastic replica technique in order to detect fatigue crack formation from the edge of the initial FIB-ed notch.

3. Results and discussion

3.1. S–N curve and residual stress relaxation

Fig. 3a and b shows the S–N curves of the SP and un-peened (UP) specimens, and the relative surface residual stress