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Fatigue crack growth behavior in gradient microstructure of hardened surface layer for an axle steel

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ABSTRACT

This paper experimentally investigated the behavior of fatigue crack growth of an axle steel with a surface strengthened gradient microstructure layer. First, the microstructure, residual stress and mechanical properties were examined as a function of depth from surface. Then the fatigue crack growth rate was measured via three point bending fatigue testing. The results indicated that fatigue crack growth rate decelerated first and then accelerated with the increase of crack length within the gradient layer. Especially, the fatigue crack was arrested in the gradient layer under relatively low stress amplitude due to the increase of threshold value for crack growth within the range of 3 mm from surface. Based on these results, the parameters of Paris equation and the threshold value of stress intensity factor range within the gradient layer were determined and a curved surface was constructed to correlate crack growth rate with stress intensity factor range and the depth from surface. The effects of microstructure, residual stress and surface notch on the crack growth behavior were also discussed.

1. Introduction

Fatigue failure is one of the main failure modes for engineering components, which has been investigated systematically since the 1860s. A large number of studies suggested that the fatigue strength of a material is proportional to its tensile strength and the fatigue crack that results in final failure usually initiates at the surface of the material [1–3]. In order to upgrade the fatigue strength of engineering materials/components, investigators have used surface strengthening techniques in the applications of aviation, automobile and high-speed railway [4–9]. The methods of surface treatment, such as shot peening, nitriding and surface induction, produce a strengthened surface layer which always possesses a gradient feature of microstructure and mechanical behavior including residual stress from the surface to the interior of treated specimens or components. Such a gradient feature must influence the fatigue crack initiation and propagation for the specimens or components.

Fajkoš et al. [5] reported that the fatigue strength of an EA4T steel (25CrMo4) with surface induction treatment had an increase of 70% compared to that with standard heat treatment. Roland et al. [7] and Yang et al. [8] showed that a stainless steel with surface mechanical attrition treatment and a pure Cu with surface mechanical grinding treatment had higher fatigue strength than the original materials, especially in high cycle fatigue regime. Other articles [10–15] also reported similar results of different materials with various types of surface treatments. All these investigations attributed the enhancement of the fatigue strength for the treated specimens or components to the grain refinement and the compressive residual stress caused by surface strengthening treatment. It has been regarded that fatigue crack growth behavior is as important as fatigue strength in the fatigue performance for a material [16,17]. With regard to the fatigue strength and the fatigue crack growth rate for the materials with different grain sizes, many articles stated that the fatigue strength of the materials with fine grains is higher than that with coarse grains, whereas the fatigue crack growth rate of the materials with fine grains is higher than that with coarse grains due to the insufficient plastic deformation ability for the fine grain cases [18–21]. Xu et al. [22] performed fatigue crack growth experiments on the steels with almost the same chemical compositions but different microstructures of pearlite-ferrite, ferrite-bainite-martensite and tempered martensite. Their result showed that the smaller the grain size was, the faster the fatigue crack grew and the higher the threshold value of stress intensity factor range (ΔK_{th}) would be. Li et al. [23] studied the fatigue crack growth behavior by modified Paris equation on a pure titanium of three different grain sizes and got the similar result of grain size effect. Blochwitz et al. [24] noticed that not only grain size but also the grain boundary influenced the fatigue crack growth for face-centered cubic metals and stainless steels. They indicated that grain boundary had an effect on fatigue crack propaga-

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tion by changing the crack path. Besides the effect of microstructure, residual stress is another significant factor that affects the fatigue crack behavior of surface strengthened materials. It was reported that compressive residual stress caused by un-uniform plastic deformation within the gradient layer, improved the fatigue resistance of 316 stainless steel, pure Cu and other alloys [7–11] and the gradient distribution of residual stress induced extra difficulty in the analysis of fatigue crack growth [25–28]. Thus, traditional fatigue theories which can describe the fatigue crack growth behavior in homogeneous materials are no longer applicable for the materials with gradient surface layer. It was anticipated that the threshold value of crack growth ΔK_{th} and the parameters of Paris equation could vary at different depths within the gradient layer [29,30]. Nevertheless, the fatigue behavior of the metallic materials containing a surface layer with gradient feature of modified microstructure is still less reported in the literature, which is a challenging topic that requires in-depth investigation, due to the related unknown mechanism and the requirement in the fatigue design of gradient materials.

Therefore, the purpose of this paper is to intensively investigate the fatigue crack growth behavior in the gradient microstructure layer of surface strengthened material. The test material is a train axle steel with surface induction treatment. Three-point bending (TPB) fatigue experiments were performed to obtain the fatigue crack growth data along the gradient microstructure layer of the specimen. The influential factors of microstructure types, microhardness, tensile strength, and residual stress at different depths of the gradient layer were characterized and used to describe the distinct behavior of fatigue crack growth in the gradient layer. The phenomena of crack deceleration and crack arrest for the gradient material were specially discussed and the notch effect on the crack growth threshold was also addressed.

2. Material and test methods

2.1. Material and specimens

The material tested in this investigation is a medium carbon steel (S38C) obtained from a high-speed locomotive axle. The chemical compositions (wt%) of this steel are: 0.42 C, 0.31 Si, 0.82 Mn, 0.0072 P, 0.0084 S, 0.02 Al, 0.0037 N, 0.0006 O and Fe balance. The axle was previously processed by induction hardening (a surface strengthening method) and thus had a gradient feature of modified microstructure surface layer.

Tensile specimens (Fig. 1(a)) were cut from an axle section gradually from surface to 7.5 mm depth with one specimen every 1 mm in depth by wire electrical-discharge machining (WEDM). The specimen cut from a given depth keeps the microstructure at that location and a series of 8 specimens from surface to 7.5 mm depth maintains the gradient microstructure feature of the material. At each depth, four specimens were prepared, i.e. 8 × 4 = 32 specimens were used in the tensile testing. All specimens were ground and polished before testing. Then, they were tested to obtain the strength and the ductility at every 1 mm depth from the surface of the material.

Specimens used for fatigue crack growth tests were also cut from the surface layer of an axle section by WEDM and every specimen maintained the gradient microstructure feature of surface layer. A notch (0.5 mm depth) was machined also by WEDM in the middle section of the specimen (hardened surface side) to lead crack initiation. The shape with the dimensions of the specimen is shown in Fig. 1(b) and (c).

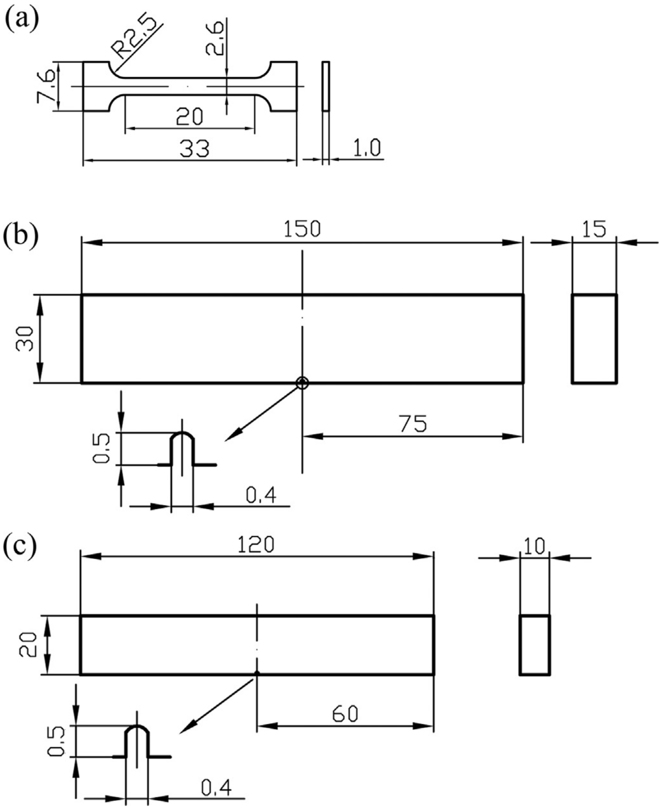

Fig. 1. Specimen shape and dimensions (in mm). (a) For tensile testing, (b) for SAL fatigue testing (loading span 120 mm) and (c) for CAL fatigue testing (loading span 80 mm).

2.2. Test methods for microstructure, microhardness, residual stress and tensile strength

The microstructure of the gradient surface layer was examined by optical microscopy. The examinations were from the surface to the interior of the material at 0.04 mm, 1 mm, 2 mm, 2.5 mm, 3 mm, 4 mm, 6 mm and 8 mm depth from surface. Five different locations were examined i.e. 5 × 8 = 40 samples were cut from the hardened surface layer accordingly and then polished and etched by 4% Nital.

The values of microhardness for the gradient surface layer were measured by using a microhardness tester. For this purpose, 5 samples were used and the measurements for each sample were from just underneath the surface down to 8 mm depth from the surface with the step of 0.5 mm between two measurements. The indentation load was 200 gf and the load maintaining time was 15 s.

The values of residual stress from the surface to the interior of the tested material were measured by using an X-Ray stress analyzer. Six SAL specimens (Fig. 1(b)) and six CAL specimens (Fig. 1(c)), three with induced notch and the other three without for each type, were used in this measurement. For notched specimens, the measurement location was from the notch root to the other end of specimen. For un-notched specimens, the measurement location was from the hardened surface to the other end of specimen.

The tensile tests on eight groups of specimens, with each group consisting of four ones (Fig. 1(a)), were performed by using an MTS testing machine (capacity 50 kN) at the tensile strain rate of 1.67×10^{-4} s^{-1}. Such specimens were cut successively from surface to different depths of 0.5 mm, 1.5 mm, 2.5 mm, 3.5 mm, 4.5 mm, 5.5 mm, 6.5 mm and 7.5 mm.

2.3. Test method for fatigue crack growth measurement

Fatigue crack growth testing was conducted at room temperature with TPB loading by means of step amplitude loading (SAL) method and constant amplitude loading (CAL) method. SAL testing was on an electromagnetic fatigue testing machine (EFTM) (Fig. 2), and CAL testing was on EFTM and MTS. The loading frequency was about 145 Hz for EFTM and 15 Hz for MTS. The stress ratio was 0.1 for both testing cases. The fatigue crack was perpendicular to the surface of the