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Improvement of the bending fatigue resistance of the hyper-eutectoid steel wires used for tire cords by a post-processing annealing

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Abstract

In this study, the effects of annealing at a low temperature on the bending fatigue resistance have been investigated in the hyper-eutectoid steel wires drawn to an extreme strain of 4.12. The annealing temperature was varied from 100 to 500 °C. The bending fatigue resistance of the steel wires was measured by a Hunter rotating beam tester specially designed for thin-sized steel wires. The results showed that fatigue resistance as well as tensile strength improved as the annealing temperature increased up to 200 °C (Region I) and gradually decreased after annealing above 200 °C (Region II). In order to elucidate this behavior, residual stress was measured by dual beam FIB, surface defects observed by an optical 3D profiler and the microstructure in terms of lamellar spacing (λ_p) and cementite thickness (t_c) was observed by TEM.

Keywords: Post-processing annealing; Hyper-eutectoid steel wire; Fatigue resistance; Residual stress; Surface defect

1. Introduction

High carbon pearlitic steel wires are usually twisted together to form the steel cords used for truck/bus radial (TBR) tires due to their outstanding strength as well as acceptable ductility [1–3]. The steel wires are generally produced via several steps of cold drawing from wires containing 0.6–0.9 wt.% C and patenting to produce a fine pearlite microstructure. In response to the market trend toward lighter, higher performance tires, the strength required for the steel wires has increased. Over the past few years, many efforts have been made to improve the strength, and strength exceeding 5400 MPa has been reported recently [2,3]. To increase the strength, it is necessary to decrease the lamellar spacing (λ_p) and to increase the drawing stain (λ) in accordance with the following Embury–Fisher equation [4]:

$$\sigma = \sigma_0 + \frac{\kappa_p}{\sqrt{2\lambda_p}} \exp\left(\frac{\varepsilon}{4}\right)$$

where σ is the strength, σ_0 is the friction stress, k_p is the Hall–Petch constant, λ_p is the lamellar spacing and ε is the drawing strain.

Besides the strength, the steel wires also required fatigue resistance, since they are usually used in a fatigue environment. Therefore, it is imperative to study their cyclic performance or the fatigue resistance. Based on the theory proposed by Bannatine [5], the fatigue resistance has been improved by changing the manufacturing process. The drawing strain is one of the strongest factors to increase the fatigue resistance of the steel wires. It is widely known that the crucial parameters lamellar spacing [6,7], cementite dissolution [8,9] and residual stress [10,11] affecting the fatigue resistance are strongly related to the drawing strain. However, since they are inter-related, the effects and the mechanisms have been not understood yet.

The annealing at a low temperature, frequently referred to as bluing, is a suitable treatment to improve the fatigue resistance as well as the strength of the steel wires. Previously, Katagiri et al. reported the effects of bluing on the eutectoid steel wires drawn to strain of 3.5, where the fatigue resistance of the steel wire increased due to the decreased residual stress and insufficient locking of the dislocation in the high drawing stain region [6]. However, few reports related to annealing at a low temperature on the bending fatigue resistance have been presented in the area

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Table 1
Chemical composition of hyper-eutectoid steel used in this study (wt.%)

C	1.02
Cr	0.2
Si	0.24
Mn	0.27
S	0.003
P	0.009
Fe	Bal.

of the hyper-eutectoid steel wires fabricated under extremely high drawing strain of above 4.0.

The present study, thus, investigates the effects of the annealing at low temperatures from 100 to 500 °C on the bending fatigue resistance of the hyper-eutectoid steel wires drawn to a strain of 4.12. The variations of the fatigue resistance, which depends on the annealing temperature, have been investigated through FIB, optical 3D profiler and TEM. An optimum annealing temperature to obtain the best fatigue resistance is also proposed.

2. Experimental procedure

Hyper-eutectoid steel was used as a specimen in this study. The chemical composition of the steel is shown in Table 1. Steel wires were fabricated by the following procedure: 1st drawing (ϕ 5.5–3.05 mm), 2nd drawing (ϕ 3.05–1.41 mm), patenting and final drawing (ϕ 1.41–0.18 mm). The patenting consisted of ausutenitizing at 1000 °C for 22 s followed by the isothermal transformation for 10 s in a lead bath at 600 °C. The final steel wires were annealed at temperatures ranging from 100 to 500 °C for 60 s and then cooled down to room temperature in air.

The bending fatigue test was performed by using a Hunter rotating beam fatigue machine (Fig. 1) at a frequency of 60 Hz in controlled conditions (temperature = 30 °C and humidity = 25%). The fatigue limits of the steel wires were determined with a criterion of no-failure at 10^6 cycles. The steel wires 200 mm in length and 0.18 mm in diameter were also tensile tested at room temperature in a fully automated mechanical test system (ISTRON 4206) with a constant crosshead speed of 0.03 mm/s to identify the strain ageing.

To exactly measure the residual stress perpendicular to the wire axis, the dual beam FIB (SMI 3050SE) machine was used to notch the wires. The displacement field generated by the slot was measured by using VIC-2D software, which had a resolution with 1/100th in a pixel. The surface morphology was observed with an optical three-dimensional profiler (Wyko NT1100), which provides a high-resolution 3D surface measurement from sub-nanometer roughness to millimeter-high steps. Surface defects, such as grooves and broken particles, were analyzed in an area of 45 μm × 60 μm at the magnification of 105×. Profiling along the wire axis was also tried to measure the surface roughness.

Microstructural parameters, such as the lamellar spacing and cementite thickness, were identified by TEM (JEOL 2010F). The specimens for the analyses were prepared by the standard electro-polishing technique in the mixture solution of 8% perchloric acid and 92% acetic acid.

3. Experimental results

3.1. Bending fatigue resistance and tensile strength

Fig. 2 shows the bending stress vs. numbers of cycle to failure (S–N) curves of the steel wires, as measured by a Hunter rotating beam tester under the applied stress level of the 1300–1600 MPa. The fatigue resistance of the steel wires was strongly influenced by the annealing temperature. That is, an annealing treatment brings an extension of the fatigue lifetime and an increase in the fatigue limit. A steel wire without annealing had a shorter fatigue life, and the fatigue limit (ϕ_{FL}) was 1310 MPa. When the annealing temperature increased, the fatigue resistance of the steel wire is higher than that without annealing. The relationship between the fatigue limits shown in Fig. 2 and annealing temperatures are plotted in Fig. 3(a). Two distinct regions can be observed in the figure: Region I from 0 to 200 °C and Region II from 200 to 500 °C. In Region I, the fatigue limit of the steel wires increased from 1350 to 1380 MPa with the increase in the annealing temperature and then slowly decreased down to 1360 MPa. Since the fatigue limit maximum is at 200 °C, steel wires should be annealed at this temperature.

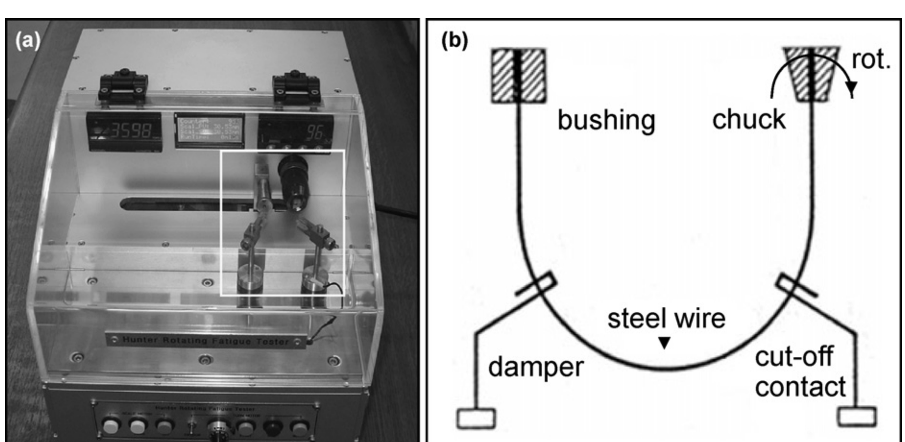

Fig. 1. (a) Automated hunter rotating beam fatigue tester, specially designed for thin-sized steel wires and (b) schematic diagram showing the several components.