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Effects of the shape of small flaws and damage due to a focused ion beam on the fatigue strength characteristics of annealed medium-carbon steel

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ABSTRACT

Fatigue tests and hardness tests were conducted in order to clarify the effects of the shapes of small flaws and damage caused by a focused ion beam (FIB) on the fatigue strength characteristics of annealed medium-carbon steel. The notch root radius of the flaw at the branch point dominates the type of the fatigue limit and was found to be approximately 50 μm, a value that was significantly smaller than the 500 μm of two-dimensional notches in steel. The effect of the FIB-damaged layer on fatigue crack initiation from the FIB-milled notch in the steel was negligible. Moreover, the present study indicated that the effect of the FIB-damaged layer on the fatigue crack initiation at the FIB-milled notch could be evaluated simply by using a hardness test for the other materials and FIB conditions.

1. Introduction

Every structural material has surface flaws introduced during the manufacturing process and regular use. Murakami et al. [1,2] investigated the effects of small flaws on the fatigue strength of various materials. Prior investigations have mainly used drilled small holes to create artificial flaws [1,2]. However, following the development of the requisite technical tools, the focused ion beam (FIB) technique has been used recently to create the artificial flaws [3–13]. The present authors investigated the effect of the flaw shape on the fatigue limit in annealed medium-carbon steel and reported that the fatigue limit of the specimens with a drilled hole was slightly higher than those of the specimens with an FIB-milled notch and a pre-crack [13].

The aim of this study was to investigate the effect of the flaw shape on the fatigue strength characteristics of annealed medium-carbon steel in detail. The initiation and propagation behaviors of fatigue cracks from a drilled hole, an FIB-milled notch, and a pre-crack were investigated using the surface observation by replica method and electron backscatter diffraction (EBSD) analysis.

One problem with the use of the FIB technique for analyzing the fatigue strength characteristics of materials is that the effects of the FIB-damaged layer on cracks initiated from an FIB-milled notch remain unclear. FIB-damaged layers of several materials (e.g., Si [14–16], Cu [17], and interstitial-free steel [18]) have been studied by transmission electron microscopy. It has been reported that the thickness of these FIB-damaged layers can be of the order of tens of nanometers [14,15,17]. The FIB-damaged layers are induced by Ga^+ ion bombardment. The thickness of the layers depends mainly on the kinetic energy and incidence angle of the used ions, and on the milling geometry. Shim et al. [19] compared the hardness values of an FIB-milled surface with an electro-polished surface of a

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Table 1
Chemical composition (wt%).

	C	Si	Mn	P	S	Al	Fe
Medium carbon steel	0.46	0.20	0.73	0.029	0.017	0.018	bal.

Table 2
Heat treatment conditions and mechanical properties of annealed medium-carbon steel.

Heat treatment	Lower yield strength, σ_y	Tensile strength, σ_B	Vickers hardness, *HV*
Annealing: 845 °C, 1 h	360 MPa	633 MPa	185 *HV*

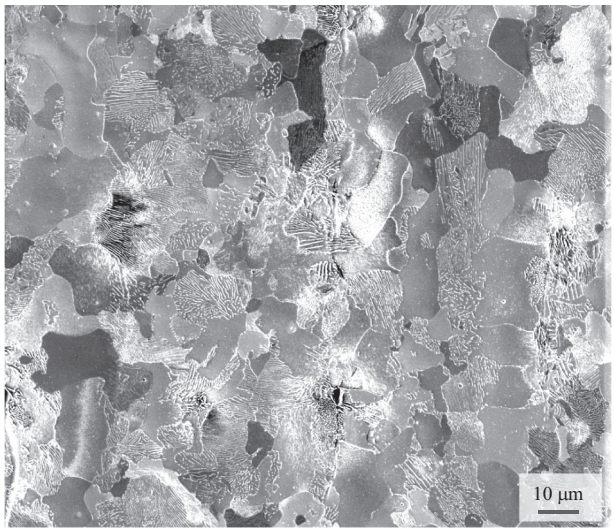

Fig. 1. SIM image of surface of annealed medium carbon steel.

single Mo-3 at.% Nb crystal via nanoindentation tests performed using a Berkovich indenter at an applied load, *F*, of 1.5 mN. The indentation depth is ~120 nm. The thickness of the damaged layer is estimated to be the order of tens of nanometers considering their stopping and range of ions in matter (SRIM) calculations. They found that FIB milling with the beam normally incident to the sample surface almost doubled the hardness of the milled surface. In other words, despite having a very low thickness, an FIB-damaged layer could increase the resistance to the crack initiation and propagation. Therefore, such layers may affect fatigue crack initiation at FIB-milled notches, which may make it impossible to evaluate the fatigue crack non-propagation limit exactly.

In this study, additional fatigue tests were conducted using specimens, which were electro-polished after the FIB-based notching to remove the FIB-damaged layer. Hardness tests were also conducted using an FIB-milled sample and an electro-polished sample. Based on the results, the effect of the FIB-damaged layer on the fatigue crack initiation from the FIB-milled notch is discussed.

2. Materials and experimental procedure

2.1. Materials

The material used in the present study was an annealed medium-carbon steel with a chemical composition summarized in Table 1. Table 2 lists the heat treatment condition and mechanical properties of the steel. Fig. 1 shows the scanning ion microscope (SIM) image of the microstructure of the steel. The microstructure consists of ferrite and pearlite. Fig. 2 shows the inverse pole figure (IPF) map of the steel. The average grain size is approximately 10 μm. Fig. 3 shows the scatter of hardness at different values of *F*. In general, hardness for mechanical properties is measured using the indenter whose indentation size is much bigger than the grain size. In this study, in order to investigate the characteristics of the microstructure, hardness is measured at relatively small values of *F*. The values of hardness are plotted on a normal probability paper, as shown in each Fig. 3(a)–(d). The hardness at $F = 0.049$ N was within