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Elucidation of the effects of cementite morphology on damage formation during monotonic and cyclic tension in binary low carbon steels using in situ characterization

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ABSTRACT

The effects of the morphology and distribution of cementite on damage formation were studied using in situ scanning electron microscopy under monotonic and cyclic tension. To investigate the effects of the morphology/distribution of cementite, intergranular cementite precipitation (ICP) and transgranular cementite precipitation (TCP) steels were prepared from an ingot of Fe-0.017 wt% C binary alloy using different heat treatments. In all cases, the damage incidents were observed primarily at the grain boundaries. The damage morphology was dependent on the cementite morphology and loading condition. Monotonic tension in the ICP steel caused cracks across the cementite plates, located at the grain boundaries. In contrast, fatigue loading in the ICP steel induced cracking at the ferrite/cementite interface. Moreover, in the TCP steel, monotonic tension- and cyclic tension-induced intergranular cracking was distinctly observed, due to the slip localization associated with a limited availability of free slip paths. When a notch is introduced to the ICP steel specimen, the morphology of the cyclic tension-induced damage at the notch tip changed to resemble that across the intergranular cementite, and was rather similar to the monotonic tension-induced damage. The damage at the notch tip coalesced with the main crack, accelerating the growth of the fatigue crack.

1. Introduction

Microstructures affect the evolution of fatigue damage and thereby influence the fatigue life and its scatter characteristics. More specifically, the initiation of fatigue cracks [1,2] and behavior of microstructurally short fatigue crack propagation [3,4] are dependent on the characteristics of the microstructure. Therefore, studying the underlying correlation between microstructural evolution and the nucleation/growth of damage has been crucial to the design of fatigue-resistant materials.

In ferritic steel, which is a major structural material, cementite is the most frequently formed second phase. Cementite precipitates both as a part of pearlite and as independent particles. Cementite particles are known to be sites where damage initiation takes place [5,6], leading to deterioration of the tensile ductility [7] and toughness [8]. On the contrary, the tensile strength [9–11] and the fatigue limit [12–14] can be improved by introducing cementite. The extent of deterioration and the observed improvement depends on the size, distribution, morphology, and volume fraction of cementite [13–15]. For instance, fatigue resistance, which is associated with fatigue crack initiation and propagation, depend on the morphology/distribution of cementite [13,14]. Moreover, the ease with which fatigue cracks initiate influences propagation behavior, as fatigue crack propagation accelerates through crack coalescence [14]. In order to maximize the positive effect of cementite and to achieve a balance between the fatigue strength and the tensile strength, it is necessary to first understand the effect of the cementite morphology on the damage formation behavior associated with monotonic tension and cyclic tension.

The factors affecting damage formation in steels are normally the boundary strength [16] (including its effect on plasticity), microstress concentration [17–19], and the accumulation of local plastic strain [20–22]. The boundary strength has been measured by mechanical testing using a single/bicrystal including a specific

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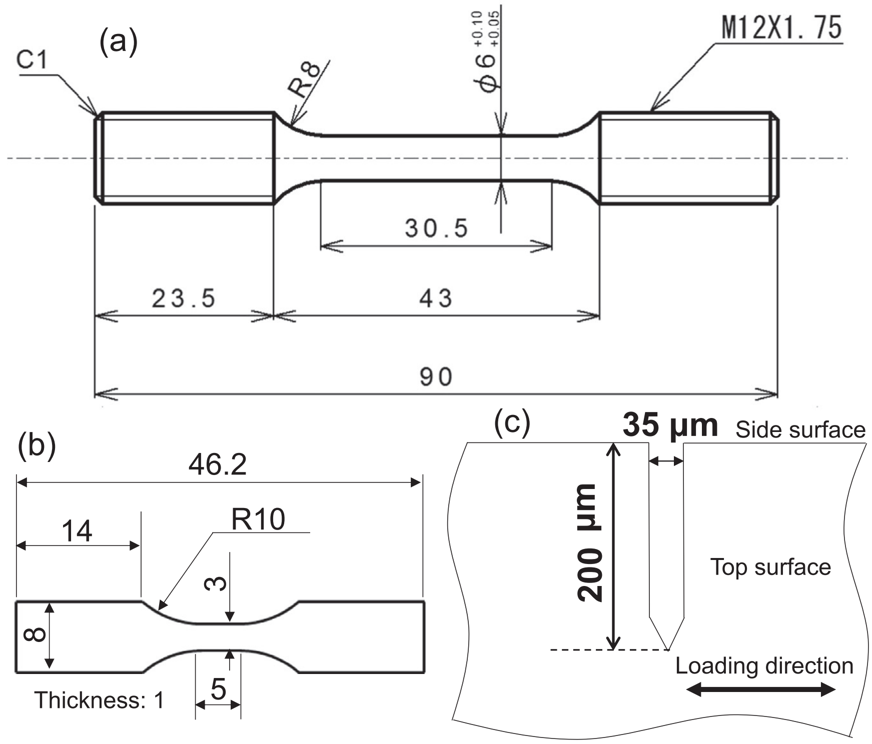

Fig. 1. Sample geometries of (a) monotonic tensile test and (b) in situ tensile and fatigue tests. Unit: mm. (c) Notch geometry for the in situ fatigue specimen.

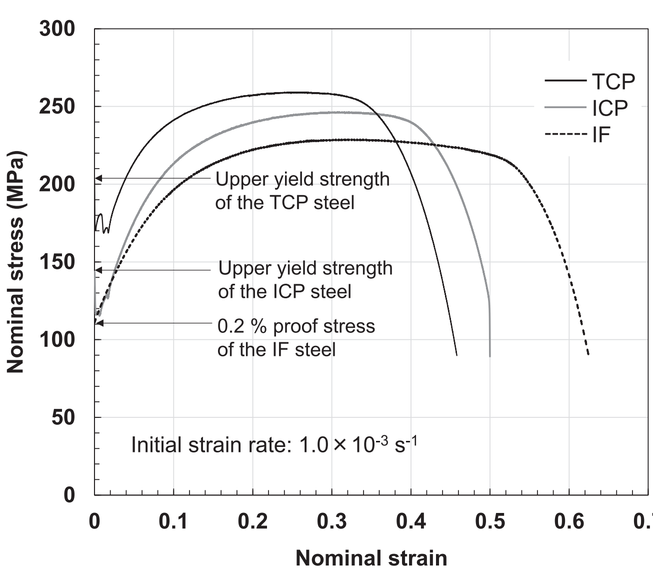

Fig. 2. Nominal stress-strain curves for the three types of steels.

phase/grain boundary [23,24] or by micro-mechanical testing [25,26]. In contrast, the effects of an identical second phase on the stress and plastic strain concentrations have been quantitatively discussed using results from in situ experiments and simulation [19]. All of these experiments and simulation require identifying the site where the primary damage occurs, and clarifying the associated behavior for the target steel under the required external conditions. However, the site of damage formation and its mode of formation in steels with different cementite morphologies/distribution have not yet been fully clarified, even for monotonic tension.

To consider the dependence of the damage formation behavior on the cementite morphology/distribution, the volume fraction of cementite must be controlled, and we have to eliminate the effects due to the presence of solute atoms and other phases such as austenite and martensite. In a previous study [14], we evaluated the fatigue resistance of Fe-C binary ferritic steels with different cementite morphologies/distribution in the absence of carbon in the solid solution. In the steel that was studied, the carbon in the steel fully precipitated as cementite, and the cementite characteristics were controlled solely by heat treatment. Therefore, the steel had no solute carbon and hence, there were no differences in the volume fraction of cementite. In the present study, we aim to clarify the effects of cementite morphology/distribution on the damage formation behavior during monotonic tension and cyclic tension for carbon-controlled Fe-C binary ferritic steels. More specifically, in order to obtain direct information about damage formation, the effect of the presence of cementite in the steels is studied using in situ scanning electron microscopy (SEM).

2. Experimental procedure

2.1. Materials

We prepared two types of low-carbon steels having identical chemical composition, but containing cementite with differing morphologies. The chemical composition in wt% is as follows: C 0.017, Si ≤ 0.003, Mn ≤ 0.003, P ≤ 0.002, S ≤ 0.0003, Ti ≤ 0.002, Al 0.052, and N 0.0009. The different cementite morphologies consist of precipitates along the grain boundaries of approximately several μm in length and 2 μm in thickness, or those located in the interior of the grains with a size of 0.3 μm in diameter and about 1 μm interval. The preparation procedure and micrographs depicting these materials are given in a previous paper [14]. Hereafter, the two cementite morphologies described above are denoted as intergranular cementite precipitation (ICP) and transgranular cementite precipitation (TCP) steels, respectively. The average grain sizes of the ICP and TCP steels were measured to be 77 and 67 μm, respectively. Although the cementite in the ICP steel precipitated