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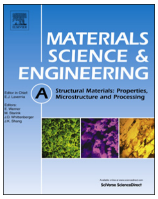

Effect of strain rate on true stress–true strain relationships of ultrafine-grained ferrite–cementite steels up to plastic deformation limit

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ABSTRACT

The true stress (σ)–true strain (ε) relationships up to the plastic deformation limit of low-carbon ferrite–cementite (FC) steels with ferrite grain sizes between 0.5 and 34 μm were estimated at strain rates between 3.3×10^{-1} and $5.0\times10^{-4}\ \mathrm{s}^{-1}$ to investigate the effect of the strain rate on the σ–ε relationship. Both σ and ε increased with increasing strain rate for each of the FC steels considered, and larger work-hardening rates were observed with increasing strain rate in the ultrafine-grained FC specimens with average ferrite grain sizes less than 1 μm. Increasing the strain rate was found to be effective in improving σ and ε up to the plastic deformation limit. The important factors in obtaining good σ–ε relationships in FC steels are the loads and the radius of curvature of the neck profile after the maximum load point. On the basis of experimental results that both σ and ε can improve under high-speed deformation such as at $10^{-1}\ \mathrm{s}^{-1}$ (as in static tensile tests) and that the decrease in ductility with increasing strain rate was small, grain refinement of up to 0.8 μm was concluded to be effective in improving the tensile deformation behavior of the low-carbon FC steels considered in this study.

1. Introduction

Ultrafine-grained steels have been widely investigated as advanced structural materials because grain refinement can achieve high strength and toughness without the addition of alloying elements [1–7]. In understanding the tensile deformation behavior of ultrafine-grained steels, it is important to understand the local deformation behavior, such as the local elongation [1,8,9] and reduction in area [10], in addition to the yield strength and uniform elongation, as discussed in previous researches [1,11–13]. Both the nominal stress–strain curve, which reflects various mechanical properties, and the true stress (σ)–true strain (ε) relationship are important in describing the deformation behavior of ultrafine-grained steels [8,14–17]. Such materials are often deformed to ε levels of more than 1.0 in various plastic working processes. Their deformation behavior at high ε levels is very important in studies of bulk nanostructured metals because of the severe plastic deformation to which they are subjected [18–22]. These extreme degrees of plastic deformation demonstrate the importance of clearly establishing the σ–ε relationship for high ε levels, i.e., exceeding 1.0 or up to fracture. We have been investigating estimates of the σ–ε relationship for ultrafine-grained steels just before fracture [8], based on studies by Bridgman [15,16], Marshall and Shaw [17], and others. In this study, we considered the limiting point, i.e., the point just before fracture at which σ can be estimated from the results of tensile tests, to be the plastic deformation limit [8,14]. We performed static and stepwise tensile tests at a strain rate of $5.0\times10^{-4}\ \mathrm{s}^{-1}$ using low-carbon ferrite–cementite (FC) steels with average ferrite grain sizes ranging from 0.5 to 34 μm and estimated the σ–ε relationships up to the plastic deformation limit [8]. The tensile test results showed that grain refinement strengthening up to 0.8 μm can improve σ and ε at the plastic deformation limit of low-carbon FC steels. We also found that the strain rate has a large effect on the flow stress of low-carbon FC steels [12,23,24]. Thus, it is necessary to investigate the deformation behavior of these steels at higher strain rates than those achievable in static tensile tests. This study was focused on the tensile deformation behavior of ultrafine-grained steels at strain rates between 10^{0} and $10^{-1}\ \mathrm{s}^{-1}$, which are relevant to seismic adequacy and various plastic working processes. In this study, the effect of the strain rate on σ–ε relationships up to the plastic deformation limit in low-carbon FC steels was investigated

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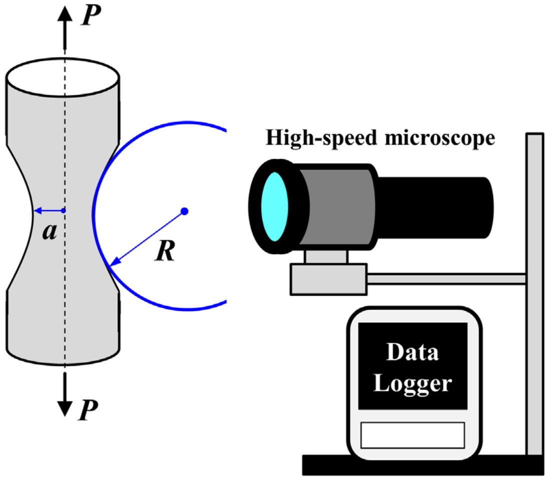
by conducting tensile tests at room temperature at strain rates between 10^{-1} and $10^{-4}\,s^{-1}$. We also examined the experimental results to determine the ferrite grain size required to obtain good tensile properties and excellent σ–ε relationships for the low-carbon FC steels considered.

2. Experimental procedures

In this study, a low-carbon steel of grade JIS-SM490 (0.15C, 0.4Si, 1.5Mn, 0.014P, 0.004S by mass%) was used to prepare FC steels with various ferrite grain sizes [8,12]. Specimens with average ferrite grain sizes between 0.5 and 34 μm were obtained by combining multi-pass-caliber rolling at warm temperatures with heat treatment [8,10,11,12]. The microstructures of the FC steels were observed using scanning electron microscopy (SEM) [8].

Round tensile test specimens with gage diameters of 3.5 mm and gage lengths of 25 mm were machined from a rolled bar 14 mm^2 [8,12]. Tensile tests were performed on the specimens at initial strain rates between 3.3×10^{-1} and $5.0\times10^{-4}\,s^{-1}$ at a temperature of 296 K, using a gear-driven-type Instron machine. Stepwise tensile test was performed to estimate the σ–ε relationships of the steels at a strain rate of $5.0\times10^{-4}\,s^{-1}$ [8]. For the tensile tests conducted at strain rates above $10^{-3}\,s^{-1}$, the changes in the dimensions of the tensile specimens during tensile deformation were recorded using a high-speed microscope. By capturing video images, we were able to measure the radius of the neck section (a) and the radius of curvature of the neck profile (R) after the maximum load point, as shown in Fig. 1. The load (P), a, and R with respect to time were determined from the results of the tensile tests, and a and R were summarized as a function of P from the results of experiments conducted using several specimens. The values of σ and ε beyond the maximum load point were calculated using the following equations. Details of the estimation of σ and ε are described elsewhere [8,14–17].

$$\sigma=\frac{P}{\pi a^2(1+(2R/a))\log(1+(a/2R))} \tag{1}$$



Radius of the neck section (a)	High-speed microscope
Radius of curvature of the neck profile (R)	
Load (P)	Data logger

Fig. 1. Schematic illustration for the measurements of load (P), the radius of the neck section (a) and the radius of curvature of the neck profile (R) in the tensile tests.

$$\varepsilon=2\ln\frac{a_0}{a} \tag{2}$$

where a_0 is the initial radius of the cross section. (In the present experimental procedure, the achievable strain rate is approximately $10^0\,s^{-1}$ [12]. To estimate the σ–ε relationships up to the plastic deformation limit at the strain rates more than $10^1\,s^{-1}$ is one of the important issues for the present study in the future.)

The cross-sectional planes in the specimens parallel to the tensile direction and near the fracture surfaces after the tensile tests were examined using SEM because ε at the plastic deformation limit (ε_{pdl}) is closely associated with the deformation of ferrite in FC steels [8]. The samples used in the SEM observations of the cross-sectional planes parallel to the tensile direction were prepared according to standard mechanical grinding and polishing procedures. Final polishing was conducted using an alumina polishing suspension, and the samples were etched using 5% Nital for approximately 10 s to reveal their microstructure. For an FC specimen with a ferrite grain size of 0.5 μm, the relationship between the deformation of the ferrite and the amount of ε was investigated by estimating ε from a in the observed region [25].

3. Results and discussion

3.1. Tensile properties from nominal stress–strain curves

Fig. 2 shows SEM micrographs of the FC steels used in this study. Elongated ferrite grains were aligned in the rolling direction, and the average cementite particle size increased slightly as the ferrite grain size increased [8,11,12]. Fig. 3 shows the nominal stress–strain curves of the FC steels for strain rates of 3.3×10^{-1} and $5.0\times10^{-4}\,s^{-1}$ [8] at room temperature. The mechanical properties of the steels at strain rates between 3.3×10^{-1} and $5.0\times10^{-4}\,s^{-1}$ are summarized in Table 1. As the average ferrite grain size decreases, the lower yield stress and tensile strength increase, and the uniform and total elongations decrease. As the strain rate increases, the strength increases and the elongations decrease. The total elongation with increasing strain rate decreases by a small percentage in the FC steels with ferrite grain sizes greater than 0.8 μm but by more than 7% in the FC steel with a ferrite grain size of 0.5 μm. A yield drop is observed in the early stage of tensile deformation in the nominal stress–strain curves of most FC steels [1,12]. However, in this study, at a strain rate of $3.3\times10^{-1}\,s^{-1}$, only the nominal stress–strain curve for the 0.5-μm FC specimen showed continuous yielding in which the load reached a maximum immediately after yielding and then decreased. That is, the type of nominal stress–strain curve was different only for the 0.5-μm FC specimen at $3.3\times10^{-1}\,s^{-1}$ [12]. As seen in Table 1, the product of tensile strength and total elongation was almost the same for the various strain rates, except for the 0.5-μm FC specimen, for which the strength–elongation balance was smaller. It is therefore difficult to discuss the effects of strain rate and ferrite grain size on tensile deformation behavior based on nominal stress–strain curves. For each FC steel considered, the reduction in area remained almost the same or increased slightly with an increase in the strain rate.

3.2. Estimated true stress–true strain relationships up to the plastic deformation limit

Fig. 4 shows estimated σ–ε relationships up to the plastic deformation limit for the FC steels considered in this study for strain rates of 3.3×10^{-1} and $5.0\times10^{-4}\,s^{-1}$ at room temperature. Fig. 5, which shows the σ–ε relationships for the FC steels with ferrite grain sizes of (a) 0.5, (b) 0.8, and (c) 34 μm at strain rates between 3.3×10^{-1} and $5.0\times10^{-4}\,s^{-1}$, illustrates the effect of the