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Dynamic deformation behavior of ultrafine-grained iron produced by ultrahigh strain deformation and annealing

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The dynamic tensile deformation behavior of ultrafine-grained interstitial free steel is shown in this paper. As the strain rate increased, the yield drop phenomenon became more significant in the stress–strain curves. The difference in flow stress between the dynamic and quasi-static strain rates did not decrease with grain refinement, in contrast to conventional high-strength steels. It is suggested that the grain refinement affected mainly the athermal component of the flow stress.

Keywords: Ultrafine-grained microstructure; Interstitial free (IF) steels; Accumulative roll bonding (ARB); Yield phenomenon; Strain rate

Ultrafine-grained (UFG) steels [1] are expected to be used in the future as structural materials, including automobile body applications, because of their superior mechanical properties. For automobile body structures, dynamic deformation properties at high strain rates are important for the passengers' safety in the case of car collisions. For evaluating the effect of the strain rate on the mechanical properties, there are two generally used indexes. One is the strain rate sensitivity parameter, m, which is described as:

$$\frac{\sigma_d}{\sigma_s} = \left(\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_s}\right)^m \tag{1}$$

where $\dot{\varepsilon}_s$ and $\dot{\varepsilon}_d$ are the strain rates at quasi-static and dynamic deformation, respectively, and σ_s and σ_d are the flow stresses at quasi-static and dynamic deformation, respectively. The other is the increase in the flow stress, $\Delta\sigma$, described as:

$$\Delta\sigma = \sigma_d - \sigma_s \tag{2}$$

In automobile body design and the management of crashworthiness, the flow stress difference, $\Delta\sigma$, is more convenient and practical. Therefore, in this paper, the $\Delta\sigma$ is discussed. We have previously reported the dynamic tensile deformation behavior of UFG low-C steel [2]. Other studies on the dynamic deformation of consolidated iron [3] and low-C steel [4] have also been reported. However, the UFG steels in those previous studies [2–4] contained some amounts of solute C, the effect of which on deformation behavior cannot be neglected. In the present study, an interstitial-free (IF) steel, where C and N are fixed as carbides and nitrides so that there is no substantial solute C and N, is used. The ferrite grain sizes are widely changed from an ultrafine size to conventional size by accumulative roll bonding (ARB) [1] and subsequent annealing. A systematic investigation of the tensile properties across a wide range of grain sizes and strain rates is carried out in this paper.

Table 1 shows the chemical composition of the commercial IF steel used in this study. Small amounts of C and N are present, but they exist as carbides or nitrides because of the addition of Ti [5].

The received steel sheets, with a thickness of 1 mm, were processed by five cycles of ARB at 500 °C. The ARB-processed sheets, still with a thickness of 1 mm, were annealed at various temperatures between 600 and 700 °C for 1.8 ks in order to change the ferrite grain sizes. Microstructures of the specimens were investigated by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). All the microstructural observations were carried out on the longitudinal sec-

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Table 1. Chemical composition of the steel studied (mass%).

C	Si	Mn	P	S	Al	Ti	N
0.002	0.01	0.17	0.012	0.007	0.033	0.047	0.003

tions perpendicular to the transverse direction (TD) of the sheets. The TEM observation was operated for both specimens before and after the tensile test. Thin foils for the deformed specimens, prepared by twin-jet electropolishing, were taken from the un-necked gauge section (about 1.5 mm far from the fractured point) of the tensile specimens after the tensile tests. In this study, mean ferrite grain sizes are represented by the mean intersect length of ferrite grains, d_t, measured on the SEM micrographs along the normal direction. Tensile properties were investigated using a high-speed servo-hydraulic material test system, which is so-called load-sensing block type equipment. Schematic illustrations of the load-sensing block and its modified version for tensile test are shown in Refs. [6] and [7], respectively. The specimen has the gauge section 2 mm in width and 6 mm in length, and two shoulder sections with holes at both ends [8]. The one end is fixed to the load-sensing block by a steel pin, the other end to a movable jig which is hit by a loading block. The displacement of the movable jig is measured by a magnetic reluctance-type position sensor. The strain of the specimen was calculated under the assumption that the displacement of the jig corresponds to the elongation of the gauge section. The tensile direction was parallel to the rolling direction of the specimens. Tensile tests were carried out at various strain rates, ranging from 10^{-2} s^{-1} to 10^3 s^{-1}, at room temperature. Total elongation of the specimens was measured from the difference in the gauge length before and after testing.

The specimens after the ARB and subsequent annealing showed ferrite single-phase matrix. As shown in the previous study [1], the specimens after ARB (which is hereafter called specimen A) and annealed at 600 °C (specimen B) had elongated ferrite grains including dislocation substructures, while the specimens annealed at 625 °C (specimen C) and 700 °C (specimen D) had equiaxed ferrite grains free from dislocation substructures. The mean ferrite grain sizes, d_t, are shown in Figure 1. Figure 1 shows representative nominal stress–strain curves of the specimens at various strain rates. The tests were carried out two or three times under identical conditions, and typical curves were selected and shown. The flow curves at 10^3 s^{-1} show oscillations. The oscillations are caused by the impact wave generated during the dynamic tensile test, and do not reflect the nature of deformation behaviors of the materials. The total elongation of specimen A increased as the strain rate increased, corresponding to the measured elongation using the specimens. However, the reason for this increase in elongation is not yet clear.

First, the yielding behavior is discussed. At the quasi-static strain rate (10^{-2} s^{-1}) yield drop phenomenon were observed in specimens A and B, which had ferrite grain sizes smaller than 1 μm, as was reported in our previous study [1]. The effect of the strain rate on the yielding behavior was slightly different between the large and small grain sizes. In specimens C and D, which had grain sizes larger than 1 μm, the yield drop phenomenon appeared only at higher strain rates (Fig. 1c and d). On the other hand, in specimens A and B, with grain sizes smaller than 1 μm, the yield drop phenomenon were observed at all the strain rates from 10^{-2} to 10^3 s^{-1} (Fig. 1a and b). The amount of yield drop (the difference between the upper yield stress (σ_{Uy}) and the lower yield stress (σ_{Ly})) was plotted as a function of the strain rate in Figure 2a. As the upper yield stress, the peak stress was taken. The critical strain rate above which the yield point phenomenon occurred increased with increasing grain size. In all the grain sizes, the yield drop became more significant

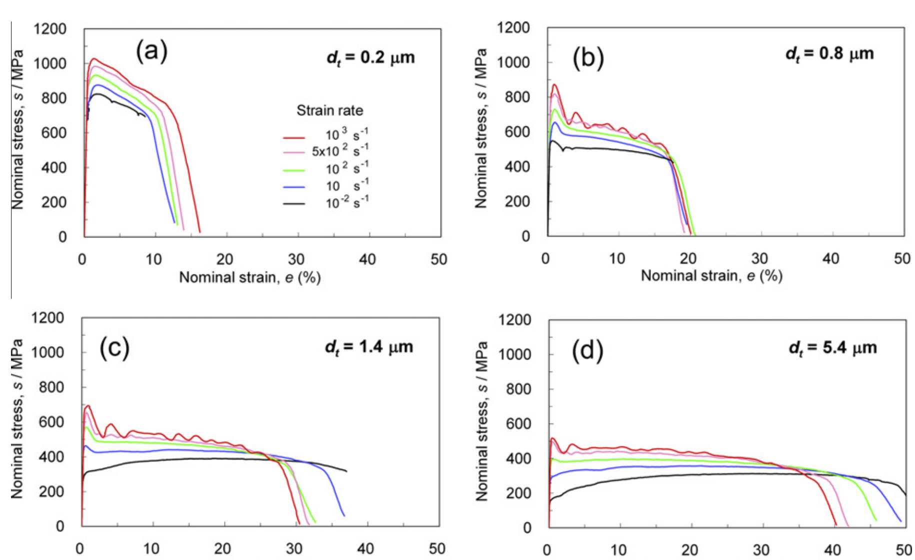

Figure 1. Nominal stress–strain curves of the IF steels: (a) as ARB processed; (b–d) ARB processed and annealed at (b) 600 °C, (c) 625 °C and (d) 700 °C. The mean ferrite grain sizes of the specimens are represented in the figures.