High-speed Deformation for an Ultrafine-grained Ferrite–Pearlite Steel

Noriyuki TSUCHIDA, Yo TOMOTA\textsuperscript{1)} and Kotobu NAGAI\textsuperscript{2)}

Domestic Research Fellow, Japan Society for the Promotion of Science, Sengen, Tsukuba 305-0047 Japan.
1) Department of Materials Science, Faculty of Engineering, Ibaraki University, Nakanarusawa, Hitachi 316-8511 Japan.
2) Steel Research Center, National Institute for Materials Science, Sengen, Tsukuba 305-0047 Japan.

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1. Introduction

To apply high-speed deformation, the material must have good ductility. However, strength and ductility have an inverse relationship, thus a good balance of strength and ductility is required in materials that can be processed with high-speed deformation. Because of dual phase strengthening,\textsuperscript{1)} the ferrite–pearlite (FP) steel has a good balance of strength and ductility that is suitable for high-speed deformation, and it is economical due to its lean alloy composition. However, the FP steel has a lower strength than the high strength steels such as the tempered martensitic steel. Ultrafine-grain strengthening is effective for increasing the strength of the FP steel without further alloying. In the conventional FP steels, the finest grain size is around 10 $\mu$m, and the minimum achievable size by the current thermomechanical control process (TMCP) is approximately 5 $\mu$m.\textsuperscript{1,2)} Recently, ultrafine-grained steels with a grain size of less than 5 $\mu$m have been developed by severe plastic deformation of low carbon steels by Nagai et al.\textsuperscript{2–4)} They reported that the ferrite–pearlite (FP) structure disappears when the ferrite grain size becomes less than 2 $\mu$m, and the ferrite–cementite (FC) structure evolves from austenite on cooling. The FC structure does not exhibit good uniform elongation, since the cementite volume fraction is too small in low carbon steels.\textsuperscript{2–4)}

The flow stress in ferritic steel is very sensitive to temperature and strain rate. Therefore, we have investigated the effect of the ferrite grain size on the static tensile properties of the FP steel at various strain rates between $10^{-6}$ and $10^{-2}$ s\textsuperscript{-1} and at various temperatures below room temperature, by varying the ferrite grain size to 3.6, 9.8 and 46.2 $\mu$m.\textsuperscript{5)} The grain size range for the conventional normal, conventional finest, and ultrafine were investigated. As a result, the FP steel with the ultrafine grain size of 3.6 $\mu$m showed a good balance of strength and uniform elongation in the static tensile test. The grain size was shown to affect mainly the athermal component of the flow stress and the thermal component was not influenced by grain refinement. Work-hardening rate increased with decreasing of temperature and was almost independent of ferrite grain size. When a plastic deformation is controlled by thermal activation theory, the effect of grain size and the work-hardening will present the same behavior at the high strain rate. The ultrafine-grained FP steel can be thereby expected to show good balance of strength and ductility at the high-speed deformation.

The present paper aimed to clarify the high-speed deformation behavior of the ultrafine-grained FP steel and to emphasize the effectiveness of the ultrafine grain FP structure on maintaining the excellent combination of high strength and good ductility. We have performed tensile tests with a strain rate of $10^3$ s\textsuperscript{-1} at low temperatures and compared the experimental results with the static test data.

2. Experimental Procedures

The FP specimens with ferrite grain sizes of 3.6, 9.8 and 46.2 $\mu$m were prepared by microstructural control for a JIS SM490 (0.15C, 0.4Si, 1.5Mn, 0.014P, 0.004S in mass%) steel. Figure 1 shows the optical micrographs of the FP specimens. The ultrafine-grained specimen with a ferrite grain size of 3.6 $\mu$m was obtained by austenitization for 3.6 ks at 1 173 K and by subsequent hot-rolling with an accumulated area reduction of 90% at 1 053 K followed by air cooling. The 9.8 and 46.2 $\mu$m FP specimens were prepared by furnace cooling after austenitization for 600 s at 1 173 K and for 5.4 ks at 1 423 K, respectively. Plate tensile specimens with a gauge length of 3.8 mm and a thickness of 1.0 mm were prepared. A Hopkinson split pressure bar tester\textsuperscript{6,7)} was used to conduct the tensile test with a strain rate of $10^5$ s\textsuperscript{-1} at 77 K (in liquid nitrogen), 210$\pm$1 K (in methanol) and 296 K (in air).

![Fig. 1. Optical micrographs of ferrite–pearlite steels with ferrite grain sizes of 3.6 $\mu$m (a), 9.8 $\mu$m (b) and 46.2 $\mu$m (c).]
3. Results and Discussions

3.1. Stress–Strain Behavior

Figures 2(a), 2(b) and 2(c) show nominal stress–nominal strain curves for the FP steels obtained from the tests using a strain rate of \(10^3\) s\(^{-1}\), and Fig. 2(d) shows an example of a flow curve at a high strain rate for a ferrite single phase steel. For the FP steels, the flow stress increases by decreasing the ferrite grain size and the uniform elongation, which is not influenced very much by the ferrite grain size, is approximately 20% at 296 K (a) and 210 K (b). Here, uniform elongation is determined by nominal strain at the maximum load. On the other hand, the flow curve for the ferrite single-phase steel is characterized by the loss of uniform elongation. This is caused by a temperature increase during high-speed deformation. The deformation is nearly in an adiabatic condition. Figure 2(d) shows that the temperature dependence of the flow stress in the ferrite phase is extremely large, thus that the flow stress decreases with straining. The introduction of pearlite colonies in the FP steel plays an important role in suppressing the decrease of flow stress because it increases the athermal component of work-hardening at 296 and 210 K. As shown in Fig. 2(c), the specimens with ferrite grain sizes of 3.6 and 9.8 \(\mu\)m fracture after a considerable amount of necking deformation (dimple fracture) while the specimen with a ferrite grain size of 46.2 \(\mu\)m shows a brittle fracture (cleavage fracture) at 77 K. The flow stress and the temperature increase due to the plastic work at 77 K are too large to suppress the loss of uniform elongation by the introduction of pearlite colonies. Uniform elongation is nearly zero for all the specimens tested at 77 K.

3.2. Effect of Grain Size on Flow Stress

Figure 2 shows that the recorded flow stress seems to be affected by the stress shock wave especially at the beginning of deformation. Therefore, a 10% flow stress (\(\sigma_{0.1}\)) is determined as the measure of flow stress in the high-speed deformation. Hence, the effect of grain size on the flow stress is discussed except at 77 K, because the data at 77 K are not enough reliable for the evaluation of the flow stress. Figure 3 shows \(\sigma_{0.1}\) at 210 and 296 K as a function of the inverse square root of the ferrite grain size (\(D\)) using the data at low strain rates for the identical steel. The Hall–Petch relation is also maintained in the high-speed deformation. The relation is given by,

\[
\sigma_{0.1} = \sigma_0 + kD^{-1/2}
\]

where \(\sigma_0\) and \(k\) are constants. The slope, related to \(k\), is insensitive to both temperature and strain rate. This means that the grain size effect only contributes to the athermal component of the flow stress and that the grain refining in-
creases the athermal component. When we imagine dislocation-emission from grain boundaries or some sources in neighboring grains, higher stress must be required in the case of shorter slip distance. That is, the smaller the grain size, the higher the athermal stress.

The thermal component can be discussed in terms of the difference in $\sigma_{0.1}$ between the flow curves at the strain rates of $10^3 \, \text{s}^{-1}$ and $10^{-2} \, \text{s}^{-1}$, and is referred as $\Delta \sigma$. The $\Delta \sigma$ usually decreases with an increase in the flow stress.\(^7\) In the present study, $\Delta \sigma$ are 124 MPa for 46.2 $\mu$m, 122 MPa for 9.8 $\mu$m, and 140 MPa for 3.6 $\mu$m at 296 K. Thus, $\Delta \sigma$ does not change from the strengthening of the present FP steel by grain refinement.

4. Summary

The flow stress for the ferrite-pearlite (FP) steels follows the Hall-Petch relationship at the high-speed deformation in the grain size range between 3.6 and 46.2 $\mu$m. Grain refinement contributes to an increase in the athermal component of flow stress and the thermal component does not decrease with an increase in the flow stress by grain refinement of the FP steel. The pearlite as the second phase increases the athermal component of work-hardening and is effective for improving the ductility of the FP steel in the high-speed deformation. Because of the grain refining and the introduction of pearlite, the ultrafine-grained FP steel shows a good balance of strength and uniform elongation in the high-speed deformation at a strain rate of $10^3 \, \text{s}^{-1}$.

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REFERENCES

1) K. Nagai: J. Mater. Process. Technol., 117 (2001), 329.
2) S. Torizuka, O. Umezawa, K. Tsuzaki and K. Nagai: Mater. Sci. Forum, 284-286 (1998), 225.
3) T. Inoue, S. Torizuka, K. Nagai, K. Tsuzaki and T. Ohashi: Mater. Sci. Technol., 17 (2001), 1580.
4) A. Ohmori, S. Torizuka and K. Nagai: CAMP-ISIJ, 14 (2001), 1128.
5) N. Tsuchida, T. Ono, Y. Tomota and K. Nagai: Trans. Jpn. Soc. Mech. Eng. A, 68-675 (2002), in press.
6) K. Miura, S. Takagi, O. Furukimi, T. Obara and S. Tanimura: SAE Tech. Pep., Ser., #960019, (1996).
7) S. Takagi, K. Miura, O. Furukimi, T. Obara, T. Kato and S. Tanimura: Tetsu-to-Hagané, 83 (1997), 748.
8) N. J. Petch: J. Iron Steel Inst., 174 (1953), 25.
9) T. Shimizu and K. Sakata: The Final Report of Research Group on High-speed Deformation of Steels for Automotive Use, ISIJ, Tokyo, (2001), 85.