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Superplastic behavior during warm deformation of martensite in medium carbon steel

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A (ferrite + carbide) microduplex structure formed by dynamic recrystallization of ferrite during warm deformation of martensite was found to exhibit superplastic characteristics. The value of $m = 0.4$ was obtained at 973 K and a strain rate of 10^{-4} s^{-1}. Microstructural analysis shows that submicron carbides are located at the ferrite grain boundary, while nanometer ones are dispersed inside ferrite grains. This kind of carbide distribution may suppress the growth of ferrite grains and form a dynamic equilibrium of average grain size during superplastic deformation.

Keywords: Superplasticity; Martensite; Dynamic recrystallization; Ultrafine-grained microstructure; Flow stress

Fine structural superplasticity (FSS) is a well-established type of superplastic behavior in polycrystalline solids. In the field of steels, many methods have been developed, such as divorced eutectoid transformation with associated deformation [1], annealing after cold rolling [2], heat treatment by multiple pass [3,4], equal channel angular pressing [5,6], and deformation-enhanced ferrite transformation [7], with the aim, first, of obtaining a fine ferrite (α) grain structure with a uniform distribution of spheroidized cementite (θ) particles (i.e., ($\alpha + \theta$) microduplex structure) and then realize FSS. The ($\alpha + \theta$) microduplex structure is beneficial for keeping a fine microstructure, because θ particles at α grain boundary are commonly considered as the obstacle for α grain growth at high temperatures. However, these methods of obtaining ($\alpha + \theta$) microduplex structure are complicated.

Recently, dynamic recrystallization (DRX) of ferrite during the warm deformation process of ferrite + pearlite structure [8,9] and martensite structure [10,11] has been studied. One advantage of DRX is the potential ability to produce an ultrafine-grained microstructure, which might be used to realize FSS. A previous study [12] showed that warm deformation of the martensite structure has more advantages than that of the ferrite + pearlite structure, owing to the reduction of critical strain necessary for generation of ultrafine-grained microstructure. Therefore, the superplasticity during the process of warm deformation of martensite deserves more attention and is worth exploring.

In this paper, an adequate pre-deformation under a strain rate of 10^{-3} s^{-1} at 1073 K (above Ae_3 temperature) is applied to the steel designed by the authors, before water quenching to obtain a finer martensite. Attention is paid to the superplastic behavior during the warm deformation process of the finer martensite. Notably, the warm deformation process in the present work is referred to as a low-rate manufacturing procedure, since the superplastic behavior is studied in terms of classical strain rate experiments. For the purpose of comparison, coarser martensite formed without undergoing pre-deformation is also discussed.

The superplastic behavior is evaluated from the strain rate sensitivity exponent (m value) and flow stress. The m value is an important parameter connected with macroscopic necking. For metallic materials, a high m value usually indicates a diffuse neck development and thus a delay of the onset of fracture, which leads to high tensile elongation [13]. Generally, a value of $m \geqslant 0.3$ is considered a superplastic characteristic.

Fe–0.47C–1.98Mn–1.37Si–0.91Cr–0.25Mo (mass%) steel (50Mn2SiCrMo) was used in this study. Specimens 8 mm in diameter and 90 mm long were cut from forging billets and then applied for pre-deformation sequence.

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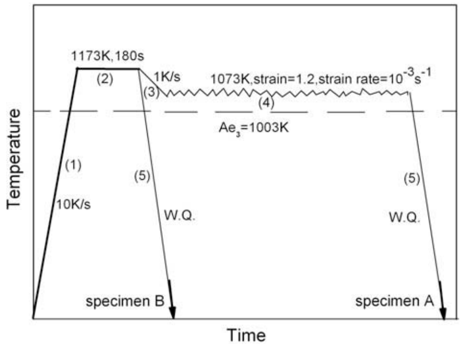

Figure 1. Thermomechanical processes of specimen A and B.

The pre-deformation sequence includes five steps (i.e., step (1)–(5)), as shown in Figure 1. After the pre-deformation sequence, specimens 6 mm in diameter and 10 mm in length (hereafter, specimen A) were cut from the central deformation part for microstructural observation and evaluation of superplastic behavior. Moreover, after undergoing steps (1), (2) and (5) (hereafter, specimen B), i.e., without undergoing pre-deformation, specimens were prepared for comparison. Both thermomechanical processes (in Fig. 1) and warm deformation processes for evaluation of superplastic behavior at 973 K (in Fig. 3) were performed by uniaxial compression test on Gleeble 1500D thermal simulator. The Backofen method was employed for the measurement of the m value. In addition, the microstructure after the warm deformation processes was focused on. Microstructural observation was conducted using transmission electron microscopy (TEM; JEOL JEM-2011) and scanning electron microscopy (SEM; JEOL JSM-6301F). The α orientation maps were measured by electron backscattered diffraction analysis.

The Ae_3 temperature of 50Mn2SiCrMo was ~1003 K. Figure 2a shows the SEM micrograph of specimen A. Almost full martensite is formed, and ferrite is not found in the microstructure. This indicates that austenite remains untransformed during pre-deformation at 1073 K (i.e., step (4) in Fig. 1) and transforms to martensite during water quenching. Figure 2b shows the stress–strain curve during step (4) in Figure 1. It could be supposed from the descending tendency of stress that austenite recrystallization occurs during pre-deformation at 1073 K. Austenite recrystallization at such a low temperature as 1073 K may reduce the size of the recrystallized austenite grains. The black dots in Figure 2a may roughly denote the center of four recrystallized austenite grains, since the austenite grain boundary could still be identified. It can be seen that the recrystallized austenite grains are relatively small (~10 μm). Figure 2c and d shows α orientation maps of specimen A and B, respectively. The martensite block of specimen A is much finer and more homogeneous than that of specimen B, which indicates that the above-mentioned pre-deformation is beneficial for obtaining the microstructure with fine and homogeneous morphology.

Figure 3a and b shows the warm deformation processes used to evaluate the superplastic behavior of specimens A and B at 973 K, respectively. A true strain of 0.04 at strain rates of 10^{-4}, 2×10^{-4}, 4×10^{-4}, 10^{-3} and 3×10^{-3} s^{-1} was applied, corresponding to stages I, II, III, IV and V. Considering that DRX of ferrite may affect the superplastic behavior, a true strain of 0.3 at 10^{-3} s^{-1} (i.e., period AB) was introduced with the purpose of showing the development of flow stress during DRX of ferrite (first period and second period are defined in Fig. 3).

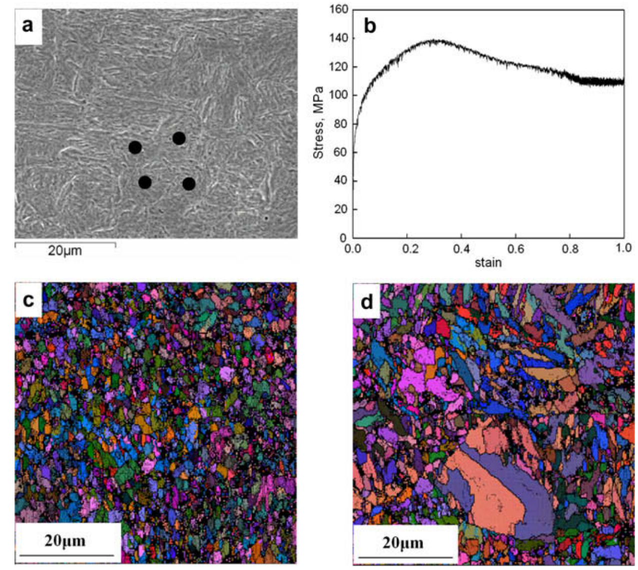

Figure 2. (a) SEM micrograph of specimen A; (b) stress–strain curve during pre-deformation at 1073 K; α orientation map of (c) specimen A and (d) specimen B.

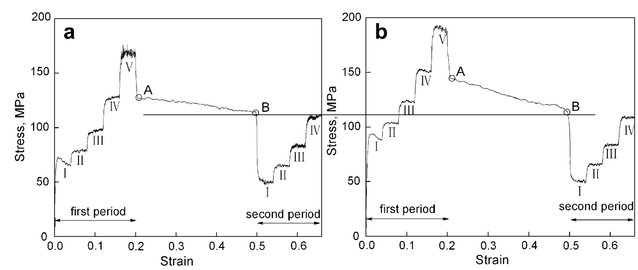

Figure 3. Warm deformation processes used to evaluate of the superplastic behavior of (a) specimen A and (b) specimen B at 973 K.

It can be seen from Figure 3 that the flow stress of specimen A is obviously lower than that of specimen B during the first period. At the end of the first period (i.e., A point), the flow stress of specimen A (127 MPa) is still lower than that of specimen B (144 MPa). This may be attributed to the fact that specimen A has a microstructure with finer and more homogeneous morphology. Owing to DRX of ferrite, the flow stress of the two specimens during period AB decreases. Noticeably, the stress downward trend of specimen B is more obvious than that of specimen A, and the flow stress of the two specimens at B point tends to be the same. In addition, the flow stress at point B is almost equal to that at stage IV of the second period for the two specimens, which indicates that DRX of ferrite might be completed at point B. Therefore, DRX of ferrite during the warm deformation process of martensite with different morphologies may end after undergoing an identical deformation process (i.e., first period + period AB in