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Influence of tempering on mechanical properties of ferrite and martensite dual phase steel

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Abstract

This study investigated the change in microstructure and mechanical properties by tempering a low carbon dual phase steel composed of ferrite and martensite. The microstructure analysis revealed that tempering process resulted in the carbide precipitation and coarsening of martensite structures. The nanohardness of each phase (martensite and ferrite) decreased with increasing the tempering temperature. The ultimate tensile strength had a linear relationship with nanohardness ratio of martensite and ferrite. On the other hand, the uniform elongation firstly did not change by tempering at the temperature below 400 °C, but then decreased by tempering at the temperature above 400 °C with decreasing the nanohardness ratio. It was concluded that the nanohardness ratio can be a good parameter for controlling the mechanical properties of dual phase steels.

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Keywords: Dual phase steel; martensite; ferrite; tensile strength; elongation; nanohardness; nanoindentation; nanohardness ratio; tempering

1. Introduction

Dual phase (DP) steels composed of a soft ferrite phase and hard martensite phase usually show a good balance of strength and ductility [1]. In addition, compared with other conventional high strength steels, DP steels satisfy some

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special properties required for good formability, such as high work-hardening rate, low yield ratio (ratios of yield strength and tensile strength), and continuous yielding [2]. In order to clarify the origin of the superior mechanical properties in DP steels, several factors such as grain sizes [3,4], martensite / ferrite strain ratio [5], volume fraction of martensite [3] and constituent phases morphology [6] have been investigated. Peng-Heng and Preban [3] found that the yield ratio decreased with increasing ferrite grain size and the ratio kept a constant value after reaching a certain ferrite grain size. Chakraborti and Mitra [2] found that the tensile strength of DP steels had a non-linear relationship with volume fraction of martensite. It has been considered that hardness of martensite is the main factor contributing to the strength of DP steels. However, difference of hardness between martensite and ferrite phases could also be an important factor for the mechanical properties of DP steels. Recently, nanoindentation technique was used to measure the nanohardness of constituent phases in DP steels. Several studies [7,8] reported that tempering decreased the nanohardness of martensite phase. Azuma et al. [9] found that the nanohardness of ferrite phase also decreased by tempering. However, Hayashi et al. [7] reported that tempering did not change the nanohardness of ferrite phase. In addition, Azuma et al. [9] found that to reduce the nanohardness difference between martensite and ferrite phases was an effective way to retard the void formation in martensite. Therefore, the present study investigated the change in mechanical properties of DP steel from a viewpoint of hardness difference between ferrite and martensite phases. The hardness ratio of two phases was changed by tempering treatments.

2. Experimental procedure

An 1.74Mn-0.75Si-0.08C steel was used in the present study. A sheet 1 mm thick of the steel was homogenized at 950 °C for 1.8 ks, followed by air cooling to obtain a microstructure composed of ferrite and pearlite. The sheet was then intercritically annealed at 840 °C (ferrite + austenite region) followed by water quenching to obtain a DP structure composed of martensite and ferrite, and then tempered at various temperatures ranging from 200 to 600 °C for 3.6 ks. All the heat treatments were carried out by a salt bath furnace. The microstructures of the specimens were observed by scanning electron microscopy (SEM, Jeol: JSM7800F). For the microstructure observations, the specimens were polished mechanically by emery papers and then electrochemically in a 10 % perchloric acid solution (100 ml HClO4+ 900 ml CH3COOH). The polished surfaces were etched in a 3 % nital solution. Tensile tests at an initial strain rate of $8.3 \times 10^{-4} \text{s}^{-1}$ were conducted at room temperature. Tensile test specimens with a gauge length of 10 mm, width of 5 mm, and thickness of 1 mm were prepared from the heat-treated specimens by spark-cutting. Nanohardness of the specimen was also measured by nanoindentation test machine (Hysitron: TI 950 TriboIndenter) with a Berkovich indenter. The loading rate was 50 μN s⁻¹, and the maximum load was 50 μN.

3. Results and discussion

3.1. Microstructure

Figure 1 shows SEM images of the specimens intercritically annealed at 840 °C (a) and subsequently tempered at 200 °C (b), 300 °C (c), 400 °C (d), 500 °C (e) and 600 °C (f) for 3.6 ks, respectively. The uneven and smooth regions in the SEM images correspond to martensite and ferrite phases, respectively. The volume fraction of martensite in the specimen intercritically annealed was 80 %. The microstructure of the specimen tempered at 200 °C (Fig. 1(b)) was similar to that of the as-quenched specimen (Fig. 1(a)). On the other hand, fine carbides precipitated in martensite after tempering at 300 °C (Fig. 1(c)). With increasing the tempering temperature (Figs. 1(d)–(f)), more carbides precipitated and carbide size increased. In addition, the substructures of martensite became coarser. After tempering at 600 °C (Fig. 1(f)), the interphase boundaries became unclear. It is expected that recovery and recrystallization of martensite happen at higher tempering temperatures.

3.2. Mechanical properties

Figure 2 (a) shows the change of elongation, i.e., uniform elongation and total elongation, as a function of tempering temperature. With increasing the tempering temperature, the total elongation monotonously increased. On the other hand, the uniform elongation did not change so much after tempering at temperature below 400 °C, while it
quickly increased above 400 °C. Figure 2(b) summarizes the change of strength (0.2% proof stress and tensile strength) as a function of tempering temperature. It is found that the ultimate tensile strength monotonously decreased with increasing the tempering temperature. On the other hand, the 0.2% proof stress firstly increased a little bit by tempering at temperatures below 300 °C, and then decreased above 300 °C. Hayashi et al. [7] also observed the increase of yield stress in DP steel by tempering. The increase of 0.2% proof stress by tempering at temperatures below 300 °C is presumably because precipitated carbides pinned mobile dislocations in martensite phase. After further tempering above 300 °C, the coarsening of carbides and martensite led to the decrease of 0.2% proof stress.

Fig. 1. SEM images showing microstructures of the specimens intercritically annealed at 840 °C and subsequently tempered at various temperatures for 3.6 Ks: (a) as intercritically annealed, (b) tempered at 200 °C, (c) tempered at 300 °C, (d) tempered at 400 °C, (e) tempered at 500 °C and (f) tempered at 600 °C. (F, ferrite; M, martensite).

Fig. 2 Change in mechanical properties in the DP steel as a function of tempering temperature. (a) uniform elongation and total elongation. (b) 0.2% proof stress and ultimate tensile strength.
Nanohardness

The nanohardness values of martensite and ferrite are shown in Fig. 3(a). The scattering of hardness in martensite is basically larger than that in ferrite. This is possibly because several boundaries inside the martensite structure, such as lath boundaries, block boundaries, and packet boundaries, could affect the nanohardness of martensite measured within a small volume. It is found from Fig. 3 that the nanohardness of both martensite and ferrite decreased with increasing the tempering temperature. In addition, the difference in nanohardness between martensite and ferrite decreased with increasing temperature. The nanohardness of martensite became similar to that of ferrite after tempering at 600 °C.

The ultimate tensile strength and uniform elongation are plotted in Fig. 3(b) as a function of the ratio of nanohardness between martensite and ferrite (M/F). The ultimate tensile strength has a linear-like relationship with the nanohardness ratio and decreased monotonously with decreasing the nanohardness ratio. The change of uniform elongation can be divided into two regions (I and II in Fig. 3(b)). In the region I (M/F < 1.34), the uniform elongation increased with decreasing the nanohardness ratio. In contrast, the uniform elongation was nearly independent of the nanohardness ratio in the region II (M/F > 1.34).

4. Conclusions

In the present study, a dual phase steel consisting martensite and ferrite was tempered for 3.6 ks at various temperatures ranging from 200 to 600 °C, and the changes of microstructure and mechanical properties with tempering temperature were investigated. The key results obtained are summarized as follows:

- The tempering treatments resulted in carbide precipitation and coarsening of martensite structure. It was suggested that finely precipitated carbides in the specimens tempered below 300 °C pinned mobile dislocations, leading to the slight increase of 0.2% proof stress.
- The nanohardness values of martensite and ferrite decreased with increasing the tempering temperature. The ultimate tensile strength monotonously decreased with decreasing the ratio of nanohardness between martensite and ferrite (M/F). On the other hand, the tendency of uniform elongation could be classified into two regions. In the region I where the hardness ratio (M/F) is smaller than 1.34 (corresponding to the tempering temperatures above 400 °C), the uniform elongation increased with decreasing the nanohardness ratio. In contrast, the uniform elongation was independent of the nanohardness ratio in the region II (M/F > 1.34, corresponding to the tempering temperatures below 400 °C).
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