Mechanical properties and characteristics of nanometer-sized precipitates in hot-rolled low-carbon ferritic steel

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Abstract: The microstructures and properties of hot-rolled low-carbon ferritic steel have been investigated by optical microscopy, field-emission scanning electron microscopy, transmission electron microscopy, and tensile tests after isothermal transformation from 600°C to 700°C for 60 min. It is found that the strength of the steel decreases with the increment of isothermal temperature, whereas the hole expansion ratio and the fraction of high-angle grain boundaries increase. A large amount of nanometer-sized carbides were homogeneously distributed throughout the material, and fine (Ti, Mo)C precipitates have a significant precipitation strengthening effect on the ferrite phase because of their high density. The nanometer-sized carbides have a lattice parameter of 0.411–0.431 nm. After isothermal transformation at 650°C for 60 min, the ferrite phase can be strengthened above 300 MPa by precipitation strengthening according to the Ashby-Orowan mechanism.

Keywords: ferritic steel; nanoparticles; mechanical properties; carbides; precipitation; strengthening

1. Introduction

It is well established that the addition of a small amount of micro-alloying elements such as niobium (Nb), vanadium (V), and titanium (Ti) into steel plays significant roles in improving its properties [1–3]. The precipitation behavior of these micro-alloying elements and their strengthening mechanisms have been investigated by many researchers [4–7]. High-strength low-alloy (HSLA) steels usually possess yield strengths of about 400–500 MPa, and the contribution of precipitation hardening to these values was considered to be minor, since many of the alloying elements were added to HSLA steels in the past basically for the strengthening of grain refinement [7]. However, in a recent study conducted at JFE steel [8], tensile strengths of up to 780 MPa have been achieved in Ti–Mo-bearing hot-rolled sheet steels by producing microstructures that consist of a ferritic matrix with nanometer-sized carbides. Precipitation strengthening due to nanometer-sized carbides in these ferrite steels has been estimated to be approximately 300 MPa, which is 2–3 times higher than that of conventional precipitation hardening in micro-alloyed steels. This value draws significant attention, and studies on nanometer-sized Ti–Mo complex carbides formed in the ferrite matrix have been reported by many researchers [9–10]. This study investigates the effect of isothermal temperature on the microstructures and properties of ferrite steel and studies the characteristics of nanometer-sized carbides precipitated in the ferrite matrix. The amount of precipitation hardening by the fine precipitates is also estimated on the basis of the Ashby-Orowan mechanism.

2. Experimental

Experimental hot-rolled ferritic steel was prepared in a 50-kg vacuum induction furnace and casted into ingots in dimensions of 60 mm × 60 mm × 60 mm (thickness × width × length). The basic composition of the investigated steel is Fe–0.043C–1.57Mn–0.088Si–0.10Ti–0.26Mo–0.007P–0.003S–0.005N (wt%), which was designed to obtain a tensile strength of around 780 MPa and a microstructure consisting of a ferritic matrix strengthened by finely precipitated carbides.

Fig. 1 shows the scheme of the hot-rolling process. The ingots were reheated at 1250°C for 90 min for solution
treatment and subsequently hot-rolled at a finishing temperature of approximately 900°C according to a thickness change of 60 mm → 42 mm → 29 mm → 20 mm → 12 mm → 6 mm → 3.2 mm. After hot rolling, the rolled plates were immediately cooled down to 600°C, 650°C, or 700°C at a cooling rate of 30°C/s and maintained at that temperature for 60 min before air cooling to room temperature.

The hole expansion test was performed in a hydraulic sheet ductility tester according to the Chinese National Standard GB/T 15825.4−2008. A hole of 10 mm in diameter is punched out and then stretched by a conic punch with the top angle of 60°. When a crack through the thickness is generated, the diameter of the expanded hole \( d \) (mm) is measured. The hole expansion ratio \( \lambda \) as an index of stretch flange formability is calculated by the following equation:

\[
\lambda = \frac{d - 10}{10} \times 100\%
\]  

Transmission electron microscopy (TEM) specimens were prepared from 0.30-mm-thick discs sliced from a mechanics performance testing specimen. The disc was thinned to 0.05 mm by abrasion on SiC paper and then twin-jet electropolished to perforation using a mixture of 5vol% perchloric acid, 5vol% glycerol, and 90vol% ethanol at 20–30°C by applying a potential of 35 V. The characteristics of the precipitated particles were examined using a field-emission-gun transmission electron microscope (FEG-TEM; JEM-2010) operated at 200 kV.

3. Results and discussion

3.1. Microstructure and mechanical properties

Fig. 2 shows the OM and SEM images of the experimental steel at an isothermal holding temperature of 600°C for 60 min. The matrix microstructure of the steel was polygonal ferrite, while pearlite and large cementite were not observed.

<table>
<thead>
<tr>
<th>Temperature / °C</th>
<th>Yield strength / MPa</th>
<th>Ultimate tensile strength / MPa</th>
<th>Elongation / %</th>
<th>Average ferrite grain size / μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>590</td>
<td>635</td>
<td>22.4</td>
<td>7.8</td>
</tr>
<tr>
<td>650</td>
<td>655</td>
<td>710</td>
<td>20.9</td>
<td>7.2</td>
</tr>
<tr>
<td>600</td>
<td>735</td>
<td>780</td>
<td>20.0</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Fig. 2. Images of the steel isothermally treated at 600°C: (a) OM and (b) SEM.