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Effect of tempering temperature on the microstructure and mechanical properties in mooring chain steel

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ABSTRACT

The tensile behavior of a mooring chain steel was investigated after tempering at 560 °C, 600 °C, 640 °C temperatures. With increasing tempering temperature, the steel displayed not only a decrease in strength, but also a slight increase in strain-hardening ability between the proof and ultimate stress. In the meantime, an upper yield point appeared at 640 °C tempered samples. The susceptibility to hydrogen-induced embrittlement reduced on the same precharging hydrogen condition as tempering temperature elevated. These changes of tensile behavior were elucidated from their microstructure variation observed by transmission electron microscopy (TEM) and electron back-scattered diffraction (EBSD).

1. Introduction

The worldwide increasing demand for oil and gas requires more energy sources at deepwater locations. Moored floating drilling vessels offer an attractive solution in a range of water depths. To ensure the safety of platform, the mooring system needs high strength. With exploring at deeper ocean, longer and longer the mooring chain requires. The mooring chain also demands higher strength to bear its adding weight. Tempering can alter strength easily for quenched and tempered steels. Unfortunately, the susceptibility of given steels to hydrogen-induced embrittlement (HIE) is generally exacerbated as their strength level rises (e.g. lowering tempering temperature) [1,2].

It has been reported that steel microstructure plays an important role in HIE [3]. Toribio [4] thought that steels with a pearlitic microstructure are more susceptible to HIE, irrespective if the steel was cold worked or hot-rolled. While, Liou et al. [5], Song and Qi [6] found that in pearlitic steels the preferred path for hydrogen diffusion are grain boundaries; therefore, pearlitic steels with big grain boundaries facilitate the hydrogen concentration if compared with the same steel with a small grain size. Sisak [7] and Marina [8] suggested that lower bainite and tempered martensite exhibit similar susceptibility to hydrogen-assisted crack initiation; however, martensite tempered at higher temperature shows the best resistance to HIE, which was attributed to the presence of very fine precipitation in its structure. In addition, untempered martensite inside the acicular ferrite-based microstructure produces a worsening of resistance of steel to HIE. Carneiro et al. [9] studied the influence of microstructure on HIE of two low C–Mn–Nb–Mo API pipe line steels, exposing the steel to different thermo-mechanical processes to modify the microstructure. The results showed that refined and homogeneous quenched and tempered bainite/martensite microstructures have the best performance with respect to HIE susceptibility. Moreover, Nanninga [2] thought that the strength level (hardness) supersedes the effects of microstructure and alloying elements in governing susceptibility to HIE after researching the degree of hydrogen embrittlement for several fastener grade steels. The degree of susceptibility of the microstructures to hydrogen embrittlement, ranked in increasing order, is as follows: fine pearlite, bainite, tempered martensite. On the contrary, Liu et al. [10] showed that hydrogen embrittlement susceptibility does not deteriorate with increase of the strength level from 1300 MPa to 1500 MPa in 3Ni–Cr–Mo–V martensitic steels through changing the Mo content from 0.43% to 1.06%. They declared that more hydrogen can be trapped by a higher amount of M_2C carbides due to its higher Mo content. Indeed, the microstructure role on hydrogen embrittlement is complicated and does not just depend on one aspect (e.g., strength, microstructure or alloying).

In the present study, three tempering temperatures were chosen to modify the microstructure of a mooring chain steel. The detailed microstructure was investigated by TEM and EBSD. At the same time, the tensile behavior and HIE were also studied after tempering at these three temperatures.

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2. Experimental procedure

2.1. Materials

The studied material is an ultra-high strength round steel as hot-rolled for mooring chain from Jiangsu Asian Star Anchor Chain Co. Ltd. (AsAc). The chemical composition is given in Ref. [11]. The subsequent heat treatment was proceeded in our laboratory. The steel was heated at 920 °C for 30 min and quenched, then tempered at 200 °C for 3 h to eliminate residual stress. Afterward, the treated bar was cut into several designed samples and these samples were tempered at higher temperature (560 °C, 600 °C and 640 °C) for 3 h to obtain different tempered microstructures, corresponding to sample codes T560, T600 and T640, respectively.

2.2. Microscopic observation

For optical observations, the microstructure was revealed by a chemical attack using a nital solution (98 mL methanol+2 mL nitric acid). EBSD analyses were performed on carefully polished specimens to diminish any surface stress. Carbides were characterized by TEM (JOEL 2010 200 kV), where very thin specimens were used in order to minimize the effect of magnetism of the sample on the electron beam. These samples were electro-polished to perforation at 243 K and 45 V using a twin-jet electropolishing unit with a solution of 10% $HClO_4$ and 90% C_2H_5OH, and then rinsed with ethanol and dried at room temperature. Post-tensile fractographic analyses were performed using a scanning electron microscope (SEM).

2.3. Mechanical tests

All tensile samples with a gage section of $16\times3\times1\ mm^3$ were polished by finer abrasive paper to remove any surface damage. Preliminary mechanical tests were performed on a MTS tensile machine at ambient temperature and at strain rate of $10^{-3}\ s^{-1}$. For hydrogen charging, samples were masked with epoxy, except at the gauge, to confine hydrogen adsorption and subsequently absorption to the gauge area. Hydrogen was introduced into the masked samples by electrochemical charging at various current densities in a solution of 1 N H_2SO_4 containing 0.05 g/l $NaAsO_3$ as a hydrogen recombination poison. The cathodic current densities were chosen in order to obtain hydrogen contents ranging in a wide interval which were able to include the embrittlement of materials (here from 0.1 to 7.5 mA/cm^2). Electrochemical charging time was chosen with respect to the saturation time depending on specimen thickness and hydrogen diffusion coefficient. After being precharged hydrogen, the samples were immediately preserved in liquid nitrogen, then tensile tested at $10^{-3}\ s^{-1}$ in order to restrict hydrogen releasing.

3. Results

3.1. Microstructures

Optical images of the microstructure for three tempered samples investigated in this study are shown in Fig. 1. The lower temperature tempered samples T560 (Fig. 1a) and T600 (Fig. 1b) have typical tempered martensite structure with lath ferrite and much finer carbides. The prior austenite grain can be distinguished from the anisotropy character and the grain size is around 13 μm. With elevating tempering temperature, the degree of anisotropy in the ferrite grain morphology for T640 (Fig. 1c) degrades and dispersed fine carbides distribute distinctly and uniformly. However, details of these dispersoids are still not resolved in these optical images in all three samples.

Fig. 2 shows bright-field TEM images of these tempered samples. An obvious difference is that the density of dislocation decreased greatly with increasing tempering temperature. T560 has acicular ferrite with a high dislocation density. The dislocation is entwisted as web. Some plates scatter long narrow shaped carbides with 80–230 nm in length and 10 nm in width (see Fig. 3a) (about 44 nm in diameter if converting oblong shape to circle by area match) and they are almost precipitated in parallel arrays at an angle of ~40° to the long direction of the acicular ferrite plates (see Fig. 3a). From its diffraction (see inset in Fig. 3b),

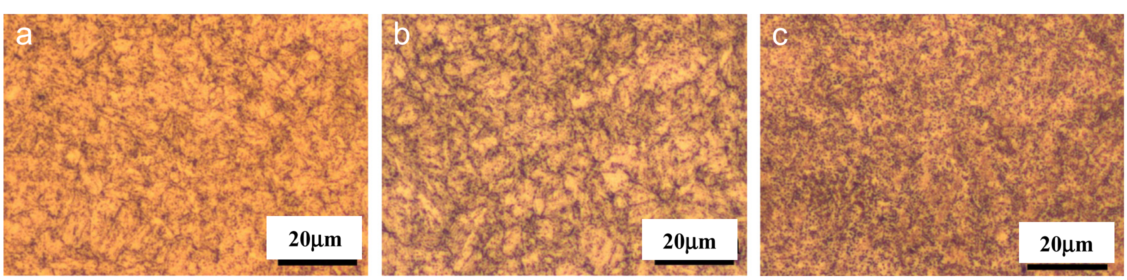

Fig. 1. Optical microstructures of the tested mooring chain steel: (a) T560; (b) T600; and (c) T640.

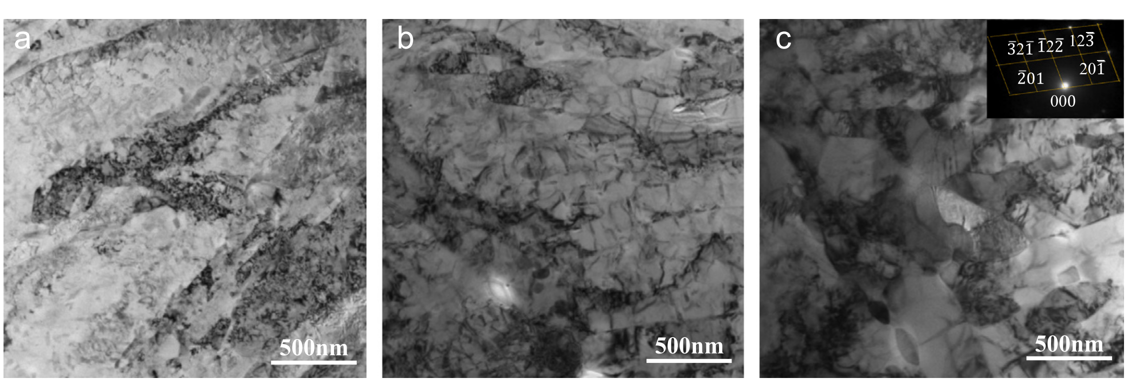

Fig. 2. TEM images of the tested mooring chain steel: (a) T560; (b) T600; and (c) T640.