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Influence of precipitation behavior on mechanical properties and hydrogen induced cracking during tempering of hot-rolled API steel for tubing

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ABSTRACT

Precipitation behavior and its effect on hydrogen embrittlement during tempering process of hot-rolled API steel designed with 0.4 wt% Cr and 0.25 wt% Mo were investigated. The base steel was normalized and then tempered at 650 °C for up to 60 min. The precipitation behavior of the examined steel was explored using transmission electron microscopy (TEM) analysis, and it was found that the precipitation sequence during tempering at 650 °C were as follows: $MX+M_3C \rightarrow MX \rightarrow MX+M_7C_3+M_{23}C_6$. The change of particle fraction was measured by electrolytic extraction technique. At the early stage of tempering, the particle fraction greatly decreased due to dissolution of M_3C particle, and increased after 10 min by the precipitation of M_7C_3 and $M_{23}C_6$ particles. The particle fraction showed a peak at 30 min tempering and decreased again due to the dissolution of M_7C_3 particle. Vickers hardness tests of base steel and tempered samples were carried out, and then the hardness was changed by accompanying with the change of particle fraction. The sensitivity of hydrogen embrittlement was evaluated through hydrogen induced cracking (HIC) tests, and the results clearly proved that HIC resistance of tempered samples was better than that of base steel due to the formation of tempered martensite, and then the HIC resistance changed depending on the precipitation behavior during tempering, i.e., the precipitation of coarse $M_{23}C_6$ and M_7C_3 particles deteriorated the HIC resistance.

1. Introduction

In recent years, the oil and gas industries have focused their efforts to investigate and develop API steel for tubing with high strength and excellent resistance to hydrogen induced cracking (HIC) in H_2S-containing sour media. Generally, when steel is exposed to aqueous H_2S, HIC occurs due to hydrogen embrittlement related to hydrogen ions (H^+) trapping during corrosion, i.e., these hydrogen ions may induce a hydrogen blister and then result in cracking by hydrogen gas penetration [1,2].

In the literatures [1–6], many researches have tried to elucidate the mechanism of HIC in steels in terms of metallurgical factors. Moon et al. [1] examined the effect of Ca treatment on HIC resistance and reported that the addition of Ca improved HIC resistance by the formation of spherical CaS inclusion instead of elongated MnS inclusion. Craig et al. [2] and Domizzi et al. [3] also investigated the effect of non-metallic inclusions on HIC. They [2] evaluated the susceptibility of hydrogen stress cracking of SAE 4130 and proved that transgranular cracking was initiated at inclusion particles during cathodic charging of specimens in three-point bending. Domizzi et al. [3] proved that the HIC susceptibility was correlated with the Sulphur content and sulphide distribution. Moon et al. [4] clearly showed that coarse (Nb,Ti,V)(C,N) complex particles can act as hydrogen trapping sites in the ferrite matrix/particle interface, resulting in hydrogen blistering. Another important factor determining HIC resistance is the microstructure of steel. Al-Mansour et al. [5] studied the sulfide stress cracking (SSC) resistance of API X100 steel and observed that HIC cracks were nucleated at banded martensite-ferrite interfaces. Park et al. [6] reported that acicular ferrite microstructure had an excellent HIC resistance.

Meanwhile, the heat treatment of quenching and tempering (QT) has been carried out to achieve the excellent HIC resistance with high strength in API steel. Carneiro et al. [7] also investigated the effect of microstructure on HIC and SSC of two low C–Mn–Nb–Mo API steel and concluded that homogeneous quenched and

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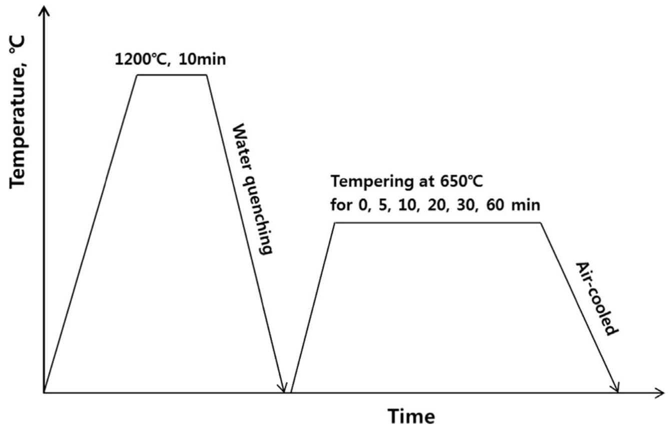

Fig. 1. Schematic illustration for heat treatment of tested alloy.

tempered bainite/martensite microstructures had the best performance for both HIC and SSC resistance. Most previous researches focused on the homogeneity of tempered microstructure, while the literature for the effect of carbide precipitation behavior on HIC resistance during tempering is lack.

Therefore, the purpose of this paper is to investigate the effect of precipitation behavior on mechanical property and HIC resistance during tempering of API steel. The microstructure evolution and precipitation behavior during tempering were carefully analyzed using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). After tempering, we evaluated the mechanical property using Vickers hardness tests and the hydrogen embrittlement using HIC tests, and finally discussed about correlation among precipitation behavior, Vickers hardness and HIC resistance.

2. Experimental procedures

The chemical composition of API steel used in this study was Fe-0.15C-0.5Mn-0.39Cr-0.26Mo-N (Ti, Nb, V, B added, wt%), and balance Fe. Base steel contained microalloying elements such as Ti, Nb and V. To obtain the hardenability during QT treatment, Mo and Cr were added. Ingot was fabricated using a vacuum-induction melting (VIM) furnace. Ingot was homogenized, and then hot-rolled into plate sample. Fig. 1 shows a schematic schedule for heat treatment after hot rolling. The sample was solution-treated for 10 min at 1200 °C and water quenched. Next, solution treated

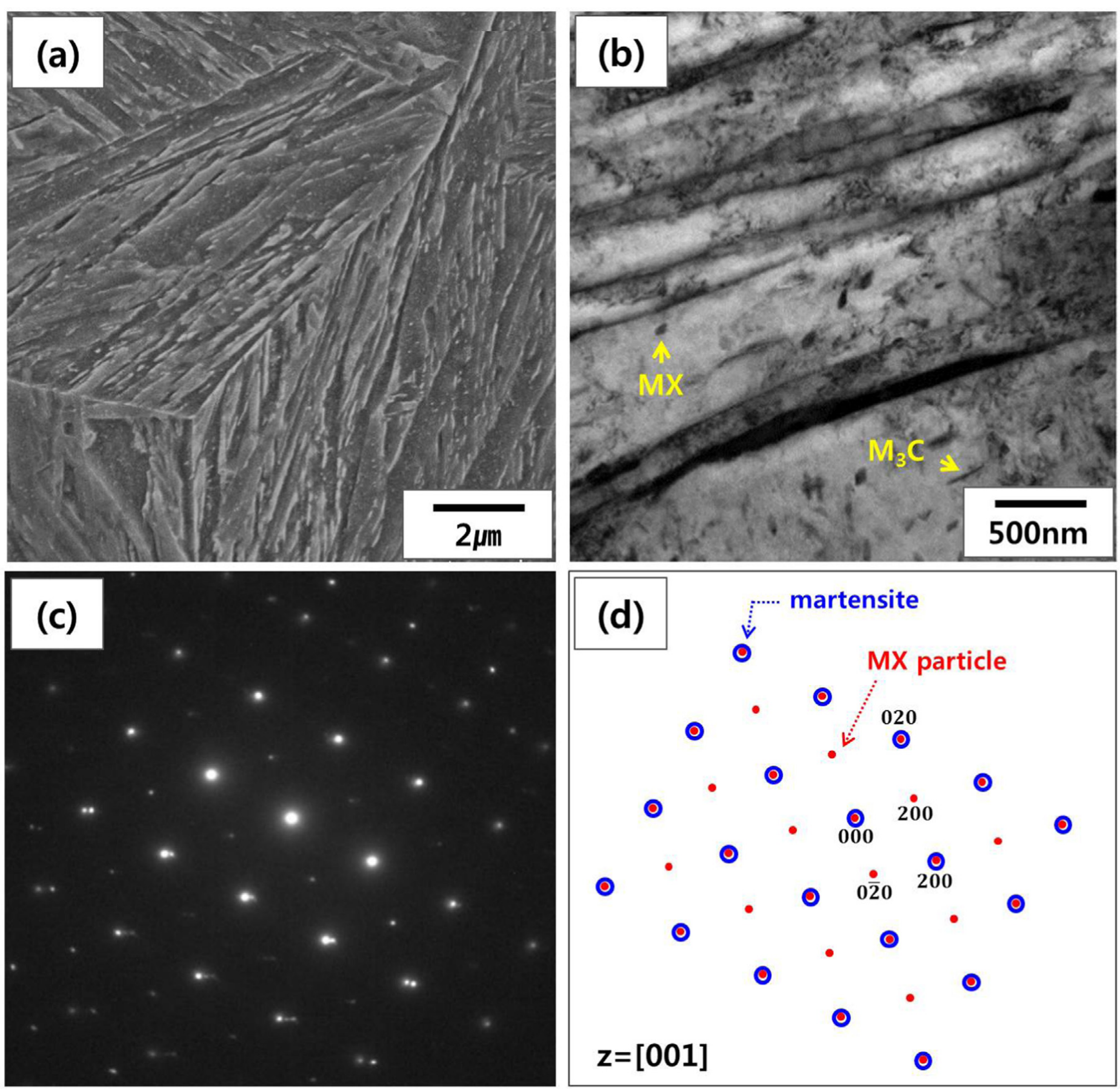

Fig. 2. Micrographs of as-quenched specimen: (a) SEM micrograph, (b) TEM micrograph, (c) SAD pattern of z=[001]$_\alpha$ and (d) a computer-simulated SAD pattern.