Effect of Deformation on Precipitation Behaviors of Carbide in Ti-Nb-Mo Steel

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Abstract. The precipitation behaviors of (Ti, Nb, Mo)C in specimens of Ti-Nb-Mo steel hold at 700 °C under no deformation condition and deformation condition with engineering strain 0.4 imposed in austenite region have been studied. The results indicate: under no deformation condition, the rows of interphase precipitation show straight and/or curve morphology, and the precipitation behaviors include interphase precipitation, random precipitation and fibrous precipitation; under deformation condition, the rows of interphase precipitation are straight, and the precipitation behaviors include interphase precipitation and strain-induced precipitation. Furthermore, the dispersion of precipitate particles formed under deformation condition is more uniform than those formed under no deformation condition.

1. Introduction

Based on the characteristics of moderate strength, good weldability and economic applicability, high strength low alloy (HSLA) steels are widely used in automobiles, bridges and other fields [1]. Alloying elements can play important roles in the controlling of microstructures and properties of steels. Since the inception of ‘Nanohiten’ steel [2], HSLA steels, such as Ti-alloyed steels, Nb-alloyed steels, Ti-Nb-alloyed steels, Ti-V-alloyed steels, in which nano-scale precipitates, in forms of interphase precipitation and/or random precipitation, can provide 200 ~ 400 MPa strength increment to yield strength, have been widely investigated for more than ten years [3]. For example, the effects of chemical composition of steels[4], cooling rate[5], final cooling temperature, holding temperature and holding time[6] on precipitation behaviors of nano-scale particles have been widely studied. Based on the reported results, it can be concluded that increasing the addition amounts of alloyed elements could attribute to obtain interphase precipitation; decreasing the final cooling temperature can increase the possibility of getting supersaturated precipitation; addition of Mo could effectively reduce the growth rate and coarsening rate of precipitation particles[7]; using continuous cooling method is favourable to get coexisting of interphase precipitation and supersaturated precipitation. Though the effects of different factors on precipitation behaviors have been studied, there is little attention focused on the effect of deformation on precipitation behaviors of (Ti,Nb,Mo)C for Ti-Nb-Mo steel. Therefore, the precipitation behaviors
2. Material and experiments

The experimental steel was melted using a vacuum induction furnace and cast as an ingot with 50 kg and subsequently forged into 80 mm × 80 mm billet. The chemical composition in weight percent of the steel is Fe-0.085C-1.8Mn-0.2Si-0.1Ti-0.1Nb-0.2Mo. A 80 mm × 80 mm × 100 mm block was cut from the billet and then homogenized at 1200 °C for 1.5 h and subsequently hot-rolled into steel plate of 15 mm thickness via six passes on the Ф450 mm two-roller reversible rolling mill.

The cylindrical specimens of diameter 5 mm and length 10 mm for experiments were machined from the center of the billet. The hot compression tests were performed on DIL805A/D and the detail experimental technologies can be seen in Fig.1. Hereafter, the specimens subjected to strains of 0 and 4mm were referred as specimen A and specimen B, respectively. The microstructures of specimens were examined by transmission electron microscopy (TEM – TECNAI-G2). Thin foils for TEM were prepared using twin-jet electrolytic thinning. The electrolyte was composed of 10% (volume fraction) perchloric acid and 90% alcohol, maintained at -25 °C, 30 V, and current of 45 mA.

3. Results and discussions

3.1. Precipitation Behaviors of (Ti,Nb,Mo)C under the Condition of no Deformation

The characteristics of interphase precipitation formed in specimen A with no deformation were presented in Fig. 2. From Fig. 2(a), it can be seen that precipitates are aligned in row regularly and this phenomenon of precipitation is referred to as interphase precipitation [8], which can be formed by ledge mechanism [9] or bowing mechanism [10]. Fig. 2(b) is the dark-field image of interphase precipitation shown in Fig. 2(a). It can be seen that the rows of interphase precipitates are not straight entirely, i.e. the rows in local areas are curved, which indicates that the interphase precipitates presented in this work are formed through both ledge mechanism and bowing mechanism of ferrite phase transformation. Bowing mechanism indicates that the driving force for ferrite phase transformation at 700 °C under no deformation condition is not sufficient enough, because the phase transformation of ferrite is keen to adopt ledge mechanism if phase transformation driving force is large enough. The sheet spacing of interphase precipitation was measured and exhibited in Fig. 2(c), from which it can be seen that sheet spacing of interphase precipitation is mainly distributed in the range of 30 nm to 38 nm, and the mean value of sheet spacing is 33.6 nm.

In addition to interphase precipitation, there are also two kinds of precipitation behaviors in specimen A, i.e. random precipitation and fibrous precipitation [11], which are shown in Fig. 3(a) and Fig. 3(b), respectively. Random precipitates, which produced in supersaturated matrix, showed aggregation
behavior in red circles in figure 3(a) and no uniform dispersion behavior in the red circle in Fig. 3(b). Fibrous precipitates, which usually appears in V-alloyed steels [11], were observed in Ti-Nb-Mo steel and showed in the red square in Fig. 3(b).

Figure 2. Interphase precipitation behaviors of (Ti, Nb, Mo) C at 700 °C under no deformation condition: (a) bright-field image of interphase precipitation, (b) corresponding dark-field image of (a) and (c) frequency distribution of sheet spacing of interphase precipitation.

3.2. Precipitation Behaviors of (Ti,Nb,Mo)C under Deformation Condition

The precipitation behaviors of (Ti,Nb,Mo)C in specimen B subjected to compression deformation of 4 mm were shown in Fig. 4, and Fig. 4(a) and 4(b) presented the bright-field image and dark-field image of interphase precipitation, respectively. It can be seen that the rows of interphase precipitation are perfectly straight, which indicates that the interphase precipitates presented in this work are formed through ledge mechanism, which indicates that the driving force for ferrite phase transformation is large enough, i.e. deformation increases the driving force. The frequency distribution of sheet spacing of interphase precipitation is shown in Fig. 4(c), from which it can be seen that the sheet spacing is mainly located in the range of 22 nm to 26 nm, which is smaller than that showed in Fig. 2(c) for interphase precipitation formed under no deformation condition, and the mean value of sheet spacing is 25.3 nm. This phenomenon also indicates that the driving force for ferrite phase transformation is higher under deformation condition than that under no deformation. This deduction is supported by Bhadeshia’s theory [12]. Apart from interphase precipitation, strain-induced precipitation [13] also observed in specimen B, which is shown in the ellipse in Fig. 4(d). Compared with the precipitation behaviors of carbide particles in specimen A, precipitates in specimen B disperse more uniformly.
Figure 3. Precipitation behaviors of random precipitation (a) and fibrous precipitation (b) of (Ti, Nb, Mo) C at 700 °C under no deformation condition.

Figure 4. Precipitation behaviors under deformation condition: (a) bright-field image of interphase precipitation, (b) dark-field image of interphase precipitation in (a), (c) frequency distribution of sheet spacing of interphase precipitation and (d) coexisting phenomenon of strain-induced precipitation and interphase precipitation.

4. Conclusion
(1) Fibrous precipitation can formed in Ti-Nb-Mo steel, and the lower phase transformation rate of ferrite, the easier the formation of fibrous precipitation.
(2) Deformation could contribute to decrease the sheet spacing of interphase precipitation.
(3) Deformation could contribute to obtain the uniform distribution of interphase precipitation and obtain strain-induced precipitation.

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