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EFFECT OF MOLYBDENUM ON PRECIPITATION BEHAVIOR IN TITANIUM MICROALLOYED HSLA STEELS PART II - PRECIPITATION DURING γ→α PHASE TRANSFORMATION

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Abstract

The effects of Mo on the isothermal γ→α phase transformation and precipitation behavior were investigated. Addition of 0.2 wt.%Mo to a Ti microalloyed steel results in a fully ferritic microstructure at higher isothermal transformation temperatures. The microhardness of the microstructure, isothermally transformed at all temperatures, in a Ti-Mo steel was higher than that in a Ti steel. This is attributed to the superior coarsening resistance of MC carbide in the Ti-Mo steel as compared with that in a Ti steel.

Introduction

Currently, an increasing number of Ti microalloyed steels are being or have been developed by many researchers, and the microstructures mainly consist of ferrite and a little pearlite. The strengthening mechanisms for these steels include grain refinement and precipitation hardening. The γ→α phase transformation process was fully used to obtain a refined ferrite grain size and a dispersion of nano-sized carbides. This microstructure exhibited a superior combination of high strength and ductility. Adding a certain amount of Mo to a Ti microalloyed steel influences the precipitation behavior of carbides during phase transformation. Firstly, the addition of Mo has an effect on the phase transformation, and then on the precipitation behavior; secondly, Mo influences the precipitation by changing the activities and diffusivities of the carbide formers; thirdly, Mo can enter the crystal lattice of MC, so leading to a complex phase transformation and precipitation process. In this paper, isothermal phase transformation experiments were conducted to study the effect of Mo on the precipitation behavior of MC type carbides.

Experimental

The chemical compositions of the studied steels are given in Table I. The Ti steel was the reference steel used to determine the role of Mo in a Ti-Mo steel. The two experimental steels were prepared by vacuum melting, and then hot forged to 20 mm diameter rods. After homogenization in the austenite phase field for 300 minutes at 1200 °C followed by water quenching, the cylindrical specimens with 8 mm diameter and 12 mm length to be used for Gleeble simulation were cut from the center of the as-homogenized rods using an electrical discharge machine. An illustration of the isothermal treatment is shown in Figure 1. The specimens were initially heated up to 1200 °C, held for 3 minutes, and then cooled to the isothermal temperature, ranging from 550 to 750 °C. The isothermal holding time was

30 minutes. After isothermal holding, the specimens were directly water quenched to room temperature. The optical metallography specimens were cut from the center of the isothermally treated specimens. The hardness of selected microstructures was measured. The hardness was measured only on the ferrite grains, when the proeutectoid ferrite was formed at higher temperature. The hardness of bainite or massive ferrite was measured under the condition that there was no ferrite formed at lower temperature. The hardness load used was 100 g and the loading time was 10 seconds. Five measurements were carried out. The precipitates were analyzed using H-800 TEM analytical and high-resolution transmission electron microscopy. EDS analysis and quantitative electron diffraction were also carried out.

Table I. Chemical Composition of Tested Steels (wt.%)

Steel	**C**	**Mn**	**Si**	**Ti**	**S**	**P**	**N**	**Mo**
Ti	0.046	1.47	0.12	0.097	0.0060	0.0073	0.0024	—
Ti-Mo	0.042	1.51	0.20	0.100	0.0028	0.0052	0.0018	0.21

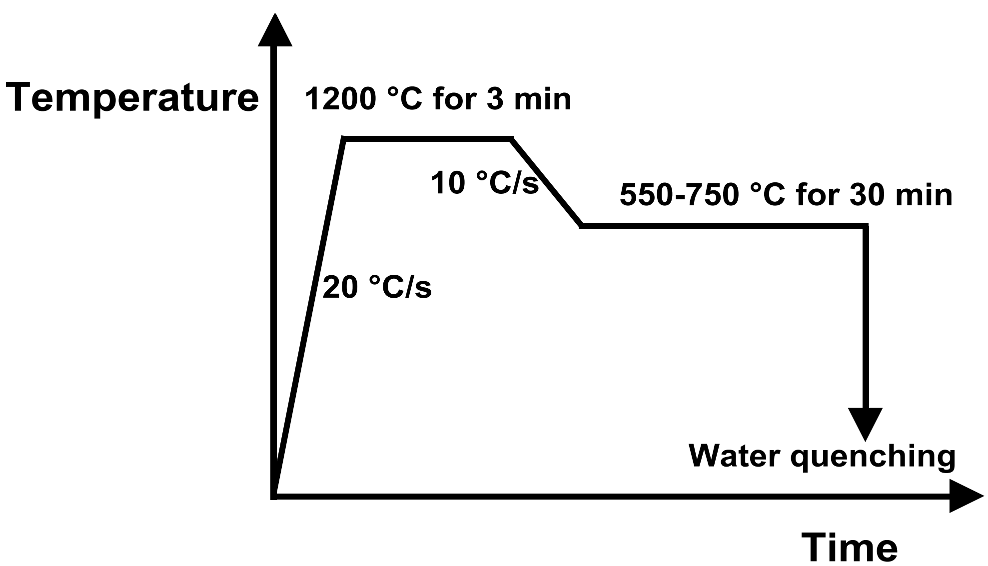

Figure 1. Illustration of isothermal treatment process.

Results and Discussion

Microstructure

Figures 2 and 3 show the isothermally transformed microstructures of the Ti and Ti-Mo steels respectively. It can be seen that the addition of Mo has a significant effect on the isothermal phase transformation of the Ti-containing steel. In the case of the Ti only steel, the transformed microstructure from 750 °C to 550 °C was: F+M(untransformed austenite) →F→M→B. In the case of Ti-Mo steel, a fully ferrite microstructure was obtained at temperatures above 725 °C. When the temperature was decreased to 700 °C, the fraction of ferrite decreased significantly. This result was opposite to that in the Ti steel. Firstly, adding Mo to the Ti steel increased the possibility of obtaining a fully ferritic microstructure. The ferrite+MC phase field was enlarged by the addition of Mo to the Ti steel, as shown in Figure 4. On the other hand, adding Mo to the Ti steel accelerates the MC precipitation during phase transformation. According to previous researchers, the addition of Mo can decrease the interfacial energy between MC and the ferrite matrix, and thus favor the nucleation and growth of precipitates during initial stages of precipitation. At higher temperatures, Mo accelerates the MC precipitation during phase transformation, thus decreasing the C content in the austenite near the γ/α interface. The decrease of C content results in the acceleration of the γ→α transformation. When the temperature was decreased to 650-675 °C, only a little ferrite was formed. This is because the diffusivity of elements at lower temperatures is very slow, resulting in the decrease of the MC precipitation rate. Under this condition, the role of Mo in delaying ferrite transformation becomes more significant. When the temperature was decreased to 625 °C or below, bainite and massive ferrite were formed.

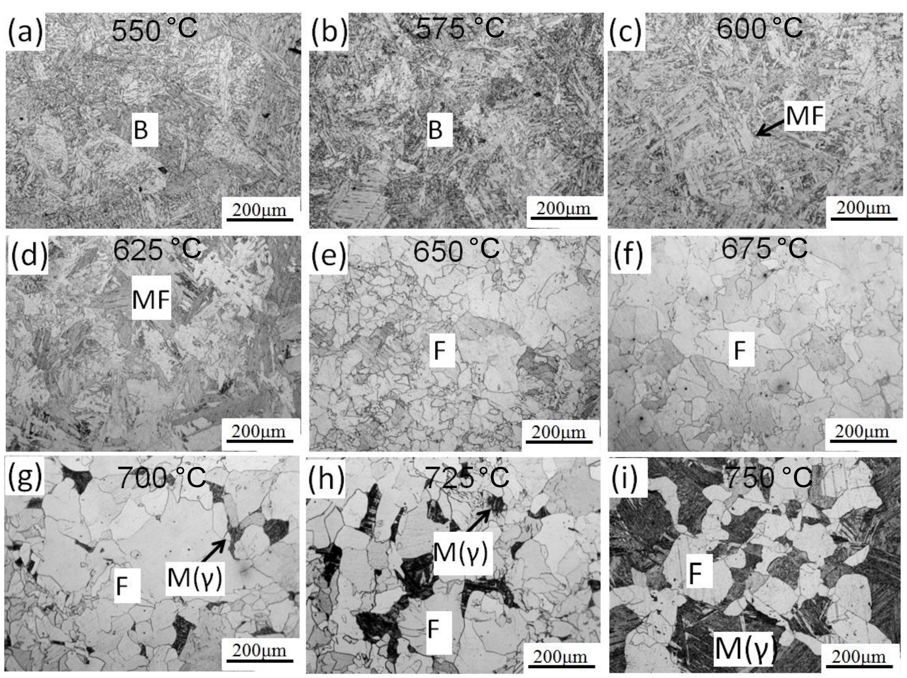

Figure 2. Transformed microstructure of Ti steel after isothermal treatment.

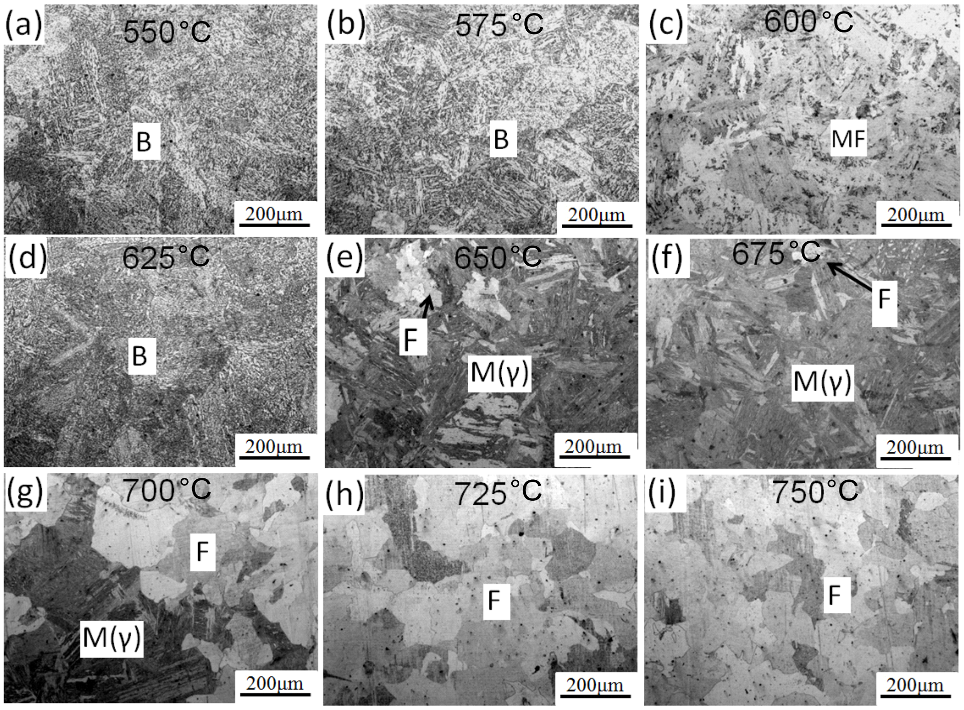

Figure 3. Transformed microstructure of Ti-Mo steel after isothermal treatment.

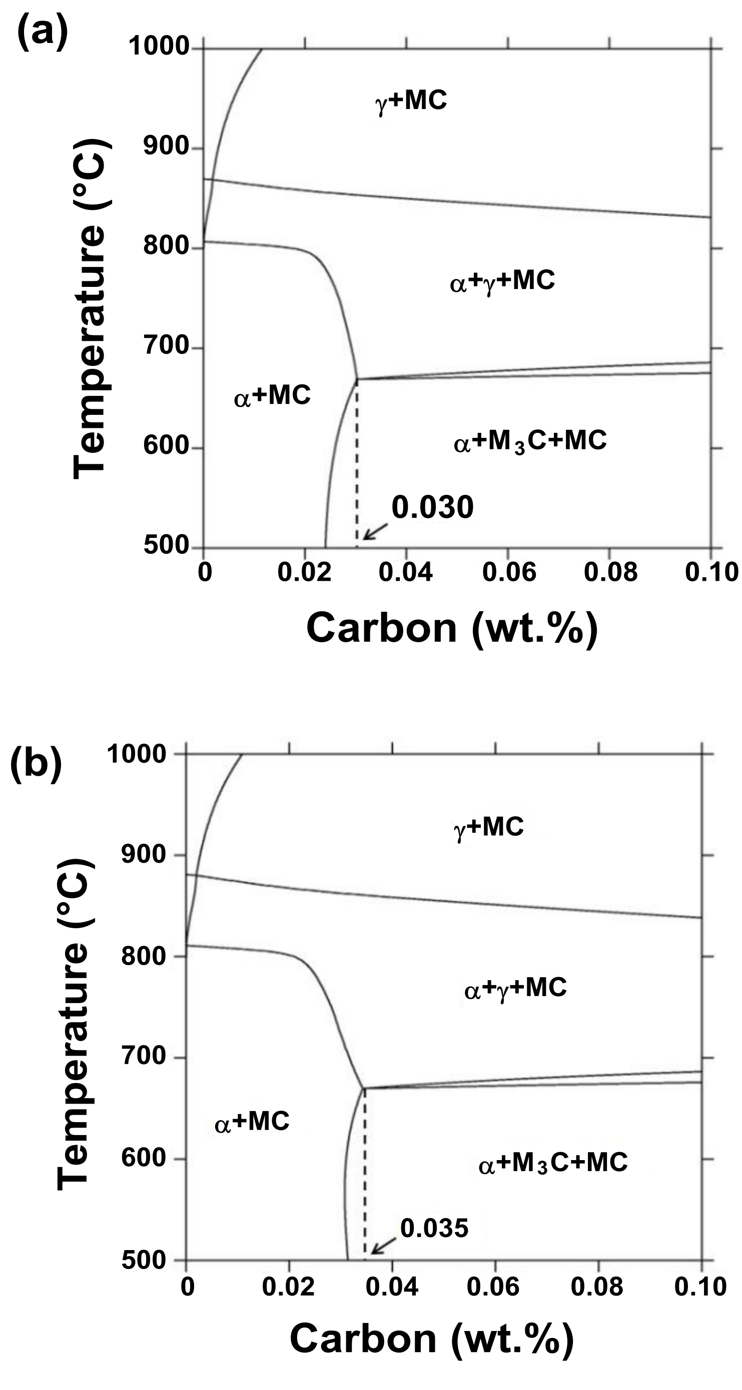

Figure 4. Phase diagram calculated using Thermo-calc (TCFE6 database);
(a) Ti steel (b) Ti-Mo steel.

Effect of Mo on the Hardness of Selected Microstructures

Figure 5 shows the hardness variation of selected microstructures of the Ti and Ti-Mo steels with isothermal temperature. It can be seen that the hardness of the Ti-Mo steel was higher than that of the Ti steel within the studied temperature range, which is evidence of increased precipitation hardening in the Ti-Mo steel.

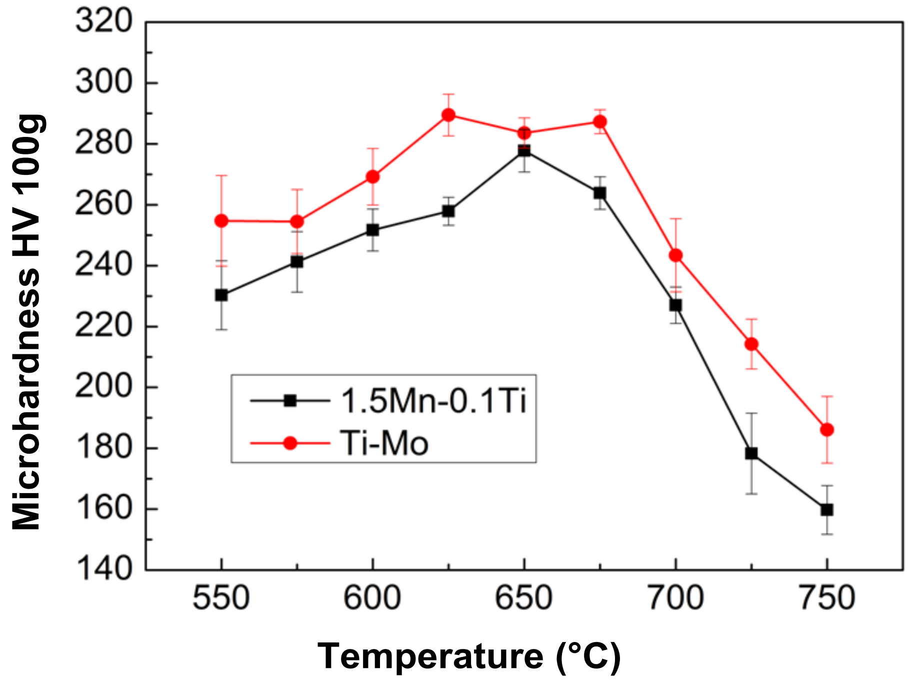

Figure 5. Effect of Mo on the microhardness of selected microstructures produced at different isothermal treatment temperatures.

Precipitates in Ti-Mo Steel and the Role of Mo

Figure 6 shows TEM images exhibiting the interphase precipitation in the Ti-Mo steel formed after an isothermal treatment at 750 °C. It can be seen that the interphase precipitation was not uniform within a ferrite grain. The finer planar-like precipitation shown in Figure 6(a) can be clearly observed. Coarser precipitates were also observed in the same grain as shown in Figure 6(b). In Figure 6(c), the interphase precipitation in a grain, having different orientations, can be observed. In addition, the precipitate size decreases with decreasing isothermal temperature, as shown in Figures 7 and 8.

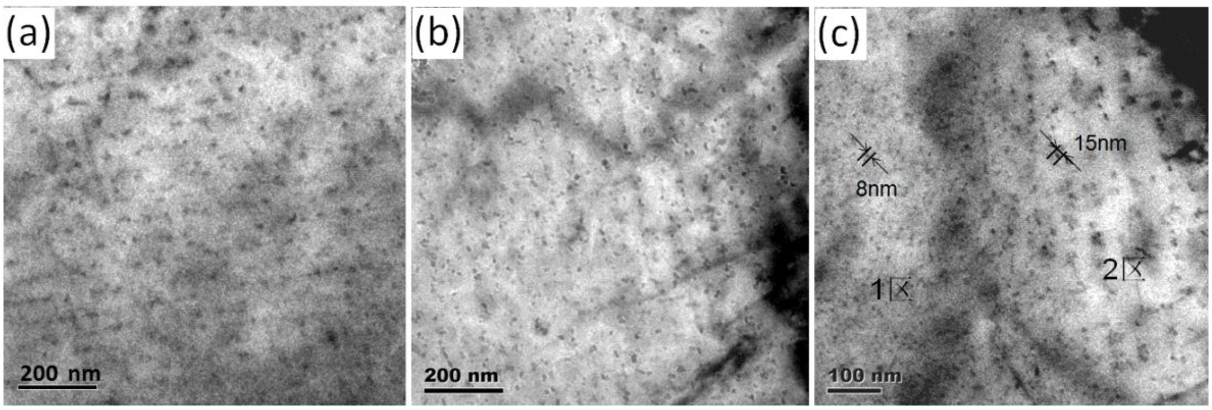

Figure 6. TEM image showing the interphase precipitation in Ti-Mo steel at 750 °C; (a) planar interphase precipitation, (b) coarser precipitates, (c) non-uniform precipitation in a grain (Area 1: fine precipitate, area 2: coarse precipitate).

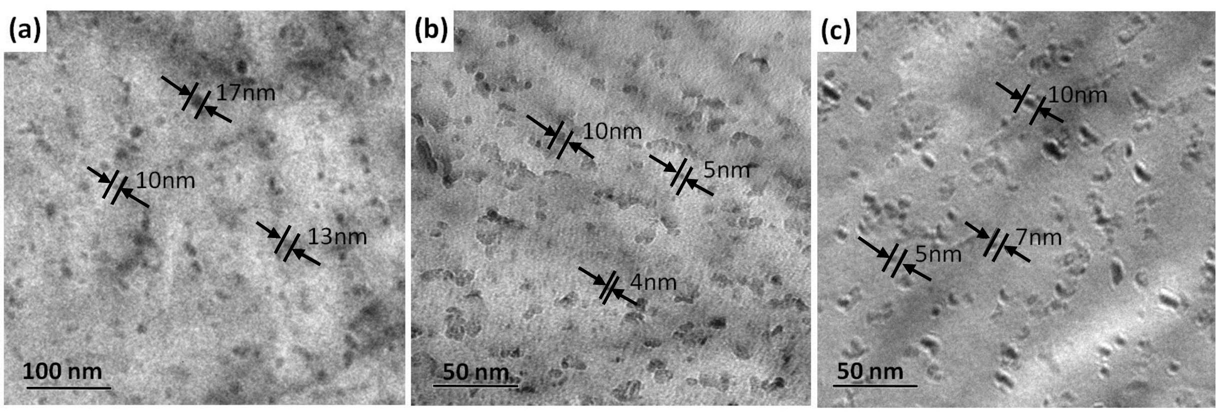

Figure 7. MC precipitate size variation with isothermal temperature; (a) 750 °C, (b) 675 °C, (c) 650 °C.

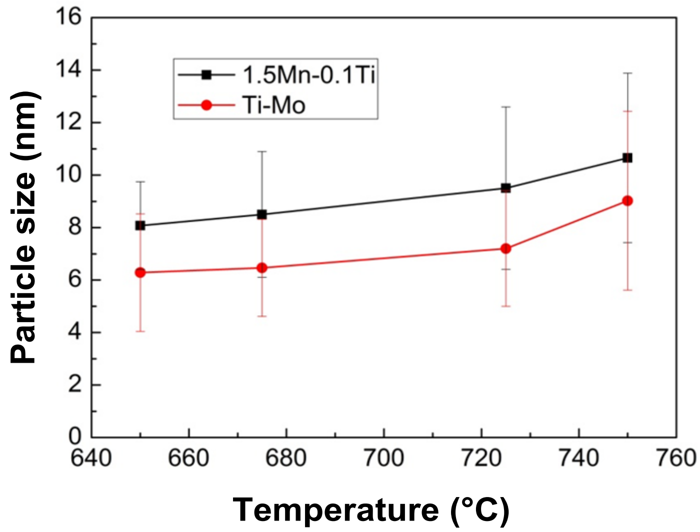

Figure 8. The effect of Mo on the precipitate size of MC carbide with variation in isothermal treatment temperature.

The selected area diffraction pattern in Figure 9(a) has been analyzed. The result indicates that (Ti,Mo) carbides forming during the isothermal transformation adopt the Baker – Nutting (B – N) orientation relationship with respect to the ferrite matrix, ie. {001}carbide//{001}ferrite and <110>carbide//<010>ferrite. The EDX spectrum shown in Figure 9(d) indicates that the content of Ti and Mo in (Ti,Mo)C was almost the same.

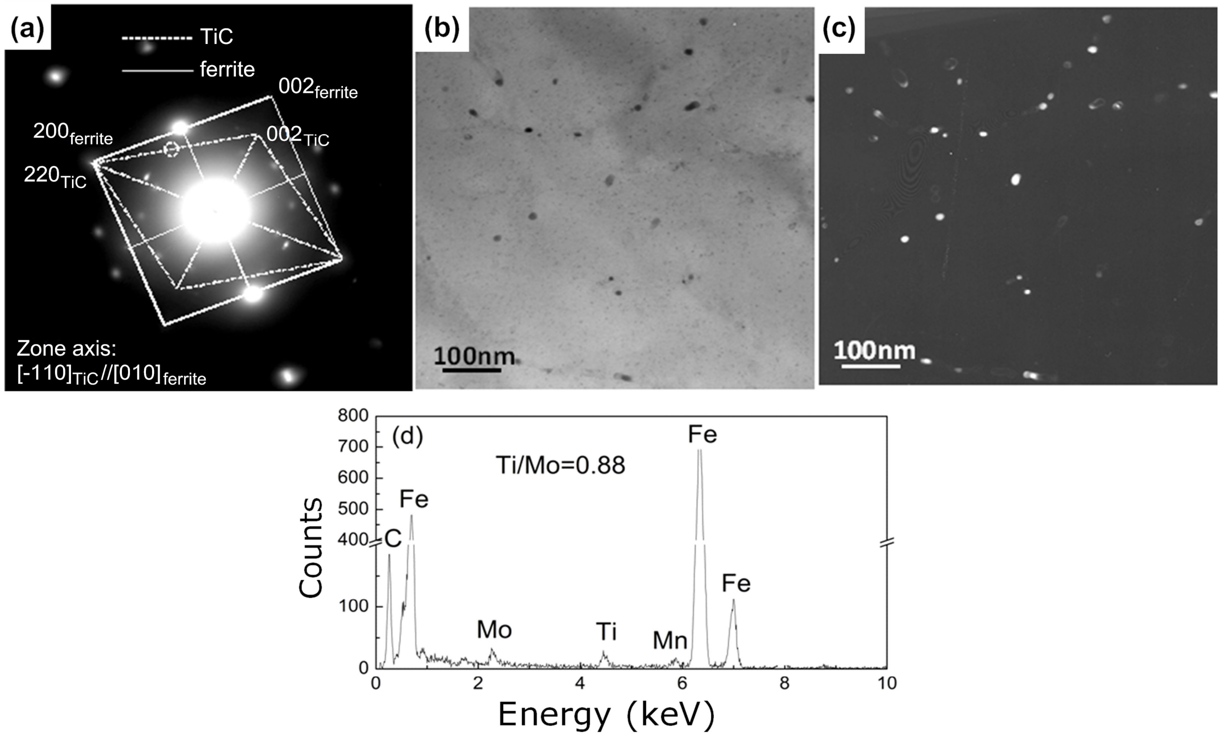

Figure 9. Crystal structure, orientation relationship with respect to the ferrite matrix and composition analysis.

Precipitation Hardening

The increase in yield strength due to the precipitation hardening can be calculated by using the following equation:

$$\Delta\sigma_p = \frac{K}{d} f^{1/2} \ln\frac{d}{b} \tag{1}$$

Where K is a constant, 5.9 N/m, b is the burger vector, f is volume fraction of precipitate and d is the average particle size. Figure 10 shows the relationship between the increase in yield strength and precipitate size. By approximate calculation, the increase in yield strength due to (Ti,Mo)C particles in the Ti-Mo steel was about 200 MPa, which is about twice the effect of TiC in the Ti steel, owing to a larger volume fraction of smaller particles.

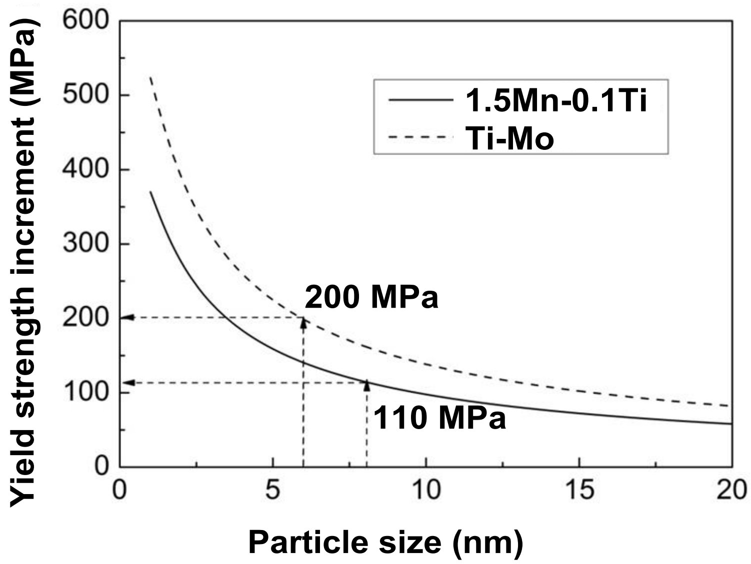

Figure 10. The relationship between the increase in yield strength and precipitate size.

Conclusions

The effects of Mo on the isothermal phase transformation and precipitation behavior in a Ti bearing steel were investigated. Addition of 0.2 wt.%Mo to a Ti microalloyed steel results in a fully ferrite microstructure at higher isothermal transformation temperatures. The microhardness of the microstructure isothermally transformed at all temperatures in the Ti-Mo steel was higher than that in the Ti steel. This is attributed to the superior coarsening resistance of MC type carbides in the Ti-Mo steel as compared with that in the Ti steel. The Ti-Mo steel exhibited an increased precipitation hardening contribution to the overall strength of the steel compared to the Ti only steel.

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