Mechanical Properties and Strength Prediction of Ti Microalloyed Low Carbon Steel with Different Ti Content

Jiakuan Ren and Zhenyu Liu*

The State Key Lab of Rolling and Automation, Northeastern University, China

*Corresponding author

Abstract. The effects of Ti on microstructures, recrystallization and mechanical properties of microalloyed low carbon steels were studied. Hall-Petch relationship and Ashby-Orowan equation were applied to analyse the reason for the variation of strength. The results show that the recrystallization activation energy increases parabolically as the Ti content increases. Besides, the yield strength, tensile strength and the yield ratio increase in varying degrees with the increasing of Ti content, while the elongation decreases. The fine grain strengthening makes the greatest contribution to the strength, and the precipitation strengthening of TiC particles is the main reason why the strength of test steel increases significantly when the Ti content exceeds 0.042%. In addition, the strength prediction model was established for Ti microalloyed low carbon steel. The relative error of predicted yield strength and tensile strength of Q345B steel are within ±8% and ±7% respectively.

Keywords: Ti microalloyed steel; Ti content; mechanical properties; precipitation strengthening; fine grain strengthening.

1. Introduction

Since the middle of the last century, microalloy elements have been added to steels to improve the mechanical properties. Microalloying technology provides a strong support for the improvement of mechanical properties of steels. Like Nb and V, added to the steels as a microalloying element, Ti can improve the properties of the steels greatly, and Ti is a strong carbide forming element, which can play a good precipitation strengthening role[1]. At the same time, single Ti microalloying can avoid mixed crystal phenomenon which is widespread in Nb microalloying[2], higher finishing rolling temperature and coiling temperature can reduce the equipment load, which makes it easier for industrial production[3,4]. Besides, Ti has unparalleled economic advantages over Nb and V. In a word, Ti microalloying technology has great potential in improving the properties of steels and green manufacturing.

The chemical properties of Ti is lively, so it’s easier to form large-volume inclusion with O, N and S, which will lead to the deteriorated performance of steels. Besides, the precipitation of TiC has a high sensitivity of temperature and cooling rate, resulting in instability of the properties of the steels. As a result, there are few applications of Ti microalloying. In recent years, with the improvement of metallurgical process and the controllability of temperature in rolling process, single Ti microalloying method has been proposed and promoted gradually. Du et al.[5] studied the nano-carbides in Ti microalloyed steels and their strengthening effects under ultra-fast cooling conditions. It was found that there were a large number of nanoscale FexC and TiC precipitates in Ti microalloyed steel. Wang et al.[6] studied the effect of Ti and Mn contents on the precipitation characteristics and strengthening mechanism in Ti microalloyed steel produced by CSP. The results showed that not only was the ratio of low-angle boundary higher, but also the number of TiC particle below 10 nm increased significantly in
the steel with higher contents of Ti and Mn. Although the studies on Ti microalloyed steel are increasing, the systematic study on the effect of different Ti content on the microstructures and properties of low carbon steel of C-Mn-Ti system remains very limited so far. According to the above reasons, five test steels with different Ti content were fabricated in this paper. The effect of different Ti content on recrystallization and mechanical properties was studied, and how the recrystallization activation energy varies with different Ti content was also investigated. In addition, the reasons for the change in mechanical properties of the test steels were calculated and analysed. Based on the traditional C-Mn steel, the strength prediction model of Ti microalloyed steel was developed, and the strength of Ti-containing steel Q345B were predicted effectively.

2. Experimental Procedures
Five 50-kg ingots of Fe-1.2Mn-0.09C-0.2Si-(0.019, 0.031, 0.042, 0.05, 0.07) Ti (wt.%) steels (hereafter, referred to as 0.02Ti, 0.03Ti, 0.04Ti, 0.05Ti, 0.07Ti steels, respectively) were melted using a high frequency vacuum induction furnace. After the ingots had been solution-treated at 1220 °C for 3 h, they were hot-rolled at temperatures ranging from ~1100 to 860 °C into a plate with 7.0 mm thickness, and ultra-fast-cooled to 640°C at a cooling rate of 35°C/s, then the plates were slow-cooled in asbestos to simulate the coiling process. The hot deformation experiment was simulated with MMS-300 thermo mechanical simulation. The specimens (size, Φ8 × 15mm) were heated to 1220 °C at a rate of 20 °C/s and kept for 3 min. Then, cooled down to 850, 900, 950, 1000, 1050, 1100 °C at a rate of 10 °C/s and compressed with a strain of 0.6 and strain rate of 0.1/s after being held for 10 s. Metallographic samples were taken from longitudinal section, and etched by 4% nitric acid alcohol solution before being analysed by Leica DM 2000 microscope. The thin foils were thinned by a Struers TenuPol-5 twin-jet electropolisher under 30 V at −25 °C in a 10.vol% perchloric acid alcohol electrolyte, and then examined in a FEI Tecnai G2 F20 field-emission transmission electron microscopy. The dog-bone-shaped tensile specimens were machined parallel to the rolling direction before testing in 30 t stretcher (WDW-300). The length, width and thickness of the gauge portion are 60, 12.5 and ~6 mm, respectively.

3. Results and Discussion
3.1. Recrystallization Behavior
The true stress-strain curves of test steels at \( \varepsilon \) (train rate) = 0.1 are shown in Fig. 1. When \( \varepsilon > \varepsilon_c \), the dynamic recrystallization kinetics equation of low carbon steel can be described as [7,8,9]:

\[
\ln \varepsilon_p = \ln (A \cdot d_0^{1/2}) + 0.15 \ln \varepsilon + 0.15 \frac{Q_d}{RT}
\]  

(1)

Where, \( \varepsilon \) is train rate, \( \varepsilon_c \) is critical train, \( \sigma_p \) is peak stress, \( \varepsilon_p \) is peak strain, \( Q_d \) are calculated as 147, 184, 194, 198, 214 kJ/mol. As the Ti content increases, the recrystallization activation energy increases parabolically. The trend is shown in Figure 1 (f), and it can be expressed as:

\[
Q_d = 71.7 + 7166.9[Ti]-54771.2[Ti]^2, \ (\text{Ti}\%<0.07)
\]  

(2)

Where \([Ti]\) is the mass percentage of Ti. The solid-solved Ti and precipitated particles could hinder the movement of dislocation and grain boundary, which inhibit the recrystallization process, so \( Q_d \) increases gradually. However, as the Ti content increases, the inhibition of the recrystallization by the solid-solved Ti and the precipitated particles is offset by the effect of refining initial austenite grain, so the rising tendency of \( Q_d \) tends to slow. For low carbon steel and C-Mn steel, the values of \( \alpha, c \) are 0.012, 0.67 respectively[10]. After further regression from the data in curves, the recrystallization volume fraction equation is as follows:
Where, \( A = 0.034 - 0.176 [\text{Ti}] + 2.448 [\text{Ti}]^2 \).

3.2. Microstructures and Mechanical Properties

3.2.1. Microstructure of Hot Rolled Plate. It can be seen from the optical microstructures in Fig. 2, when the Ti content is less than 0.042%, the grain size of test steel has little difference. When the Ti content exceeds 0.042%, the grain size becomes smaller. For phase proportion, when Ti content is lower than 0.05%, the microstructures are mainly composed of polygonal ferrite and a small amount of pearlite. When the Ti content exceeds 0.05%, a small amount of bainite appears.

3.2.2. Mechanical Properties. The mechanical properties of hot-rolled plate are shown in Table 1, as the Ti content increases, the yield strength, tensile strength and yield ratio increase gradually, while the elongation decreases gradually. When the Ti content exceeds 0.042%, the growing trend of strength is more significant.
3.2.3. Analysis of Strengthening Mechanism. For low-carbon steel, the main strengthening mechanisms include precipitation strengthening, solution strengthening and fine grain strengthening. The yield strength can be expressed as\cite{11,12}:

\[
\sigma_y = \sigma_0 + \sigma_s + \sigma_g + \sigma_d + \sigma_p
\]  

(4)

Where, $\sigma_0$ is the lattice frictional stress, and its value of low-carbon steel is 53MPa; $\sigma_s$, $\sigma_g$ and $\sigma_p$ denote solid solution strengthening, fine grain strengthening and precipitation strengthening respectively; $\sigma_d$ denotes dislocation strengthening. Due to the lower dislocation density of test steel after higher temperature coiling, the dislocation strengthening is negligible in this paper.

Fine grain strengthening can be expressed by Hall-Petch formula\cite{13,14}:

\[
\sigma_g = k_y d^{-0.5}
\]  

(5)

Where, $d$ is the average grain size of ferrite, mm; $k_y$ is the proportionality coefficient, 17.4 MPa·mm\(^{1/2}\) in low-carbon steel.

The solid solution strengthening can be expressed as\cite{15}:

\[
\sigma_s = 37[Mn] + 83[Si] + 59[Al] + 38[Cr] + 11[Mo] + 33[Ni] - 30[Cr] + 680[P] + 2918[N] + 4570[C]
\]  

(6)

Where, $[M]$ is the mass fraction of solid solution elements; $[C]$, the content of solid-solved carbon in ferrite is taken as 0.01%; the form of elements such as manganese, copper, silicon, phosphorus, in steel are solid solution state, and their chemical composition in test steel can be directly introduced into Eq. (6).

However, Ti can easily combine with C and N to form compounds. According to the solubility product of TiN (Kunze, 1982) and TiC (Tayor, 1995) in austenite, when the coiling temperature exceeds 600 °C, the solid solubility of TiN and TiC in austenite are \(~2.8\times10^{-13}, ~5.4\times10^{-6}\) respectively, this value is lower in ferrite. Besides, even in the case of low Ti content, N could combine with Al to form AlN, so the content of dissolved N in steel is very low. As a result, the solid solution strengthening effect of Ti and N are negligible.

For precipitation strengthening, Ti(C, N) belongs to the hard phase. When the precipitated phase is deformed, the dislocation almost can not cut it off. Therefore, its strengthening mechanism is Orowan strengthening theory of non-deformable particles, the strengthening mainly comes from the additional stress caused by dislocations bending around the precipitation phase and leaving Orowan dislocation loops\cite{16}. It can be expressed by the Ashby-Orowan model\cite{17}. In this paper, the shear modulus of matrix $G = 80300\text{MPa}$ and the Burgers vector $b = 2.5 \times 10^{-4} \mu m$ were substituted into the model\cite{18,19}:

\[
\Delta \sigma_p = \left( \frac{10.8 f^2}{X} \right) \ln \left( \frac{X}{6.125 \times 10^{-4}} \right)
\]

(7)

Where $X$ is the average diameter of the precipitated phase. According to TEMs statistics, X is determined as 0.01 μm; $f$ is the volume fraction of precipitation phase. The solubility of TiN in austenite is very low. Under soaking conditions, the solid solubility of TiN in austenite at 1220 °C is only $6.5\times10^{-6}$. It is considered that most of TiN particles have precipitated from the austenite. The precipitated TiN particles will coarsen during the cooling process of vacuum melting. Hence, the TiN particles is weak in precipitation strengthening, and the precipitated particles dominant in precipitation strengthening is TiC. Its volume fraction can be expressed as \cite{12}:

\[
f = \left( Ti - [Ti] \right) \frac{A_Ti}{A_C} + \frac{d_{Fe}}{100d_{TiC}}
\]

(8)

Where, $A_{Ti}, A_C$ are the atomic weights of Ti, C respectively; $d_{Fe}, d_{TiC}$ are the density of the iron matrix and the TiC phase, taken as 4.944g / cm\(^3\) and 7.88g / cm\(^3\), respectively; $[Ti]$ is effective titanium, which
combines with carbon to form TiC, according to the stoichiometric ratio, there is following relationship\[20\]:

\[
[\text{Ti}] = w(\text{Ti}) - 3.4w(\text{N}) - 3w(\text{S})
\]

(9)

Where, \(w(\text{Ti})\), \(w(\text{N})\), \(w(\text{S})\) are the mass percentage of Ti, N, S elements in steel.

Substituting the calculated results into Eq. (7) and (8), the results are shown in Table 1.

It can be seen from Fig. 3 (a) that the calculated yield strength agrees with the measured value basically, the calculated yield strength is slightly lower than the measured value due to the neglect of dislocation strengthening. In addition, the fine grain strengthening contributes most to the strength of the test steel, and the precipitation strengthening is the main reason for the difference of the strength of the test steel.

**Table 1. Physical parameters of test steel.**

| Steel | Ferrite \(d/\mu\text{m}\) | \(\sigma_p/\text{MPa}\) | \(\sigma_f/\text{MPa}\) | \([\text{Ti}]\)% | \(f\) | \(\Delta\sigma_p/\text{MPa}\) | Calculated \(\sigma_f/\text{MPa}\) | Measured \(\sigma_f/\text{MPa}\) | \(R_m/\text{MPa}\) | TEL/\% |
|-------|-----------------|-----------------|-----------------|----------------|---|-----------------|-----------------|-----------------|-----------------|-----|
| 0.02Ti | 8.4             | 190             | 113             | 0              | 0  | 0               | 356             | 371             | 472             | 32  |
| 0.03Ti | 8.9             | 184             | 112             | 0.0029         | 0.00006 | 23              | 372             | 387             | 488             | 29  |
| 0.04Ti | 8.7             | 187             | 112             | 0.0079         | 0.00016 | 38              | 390             | 409             | 501             | 28  |
| 0.05Ti | 7.9             | 196             | 111             | 0.0240         | 0.00048 | 66              | 426             | 444             | 525             | 26  |
| 0.07Ti | 5.6             | 233             | 112             | 0.0440         | 0.00088 | 89              | 487             | 511             | 584             | 25  |

**Figure 3.** Strength calculation results of test steels.

According to Eq. (10)[20], the equilibrium solubility of TiN at 1220°C were calculated. As shown in Fig. 4 (a), most Ti elements are still dissolved in steel, but N elements are the opposite. In addition, the theoretical precipitation temperature of TiC was calculated as 1004, 1057, 1068, 1087, 1141°C respectively. When the temperature is below theoretical precipitation temperature, TiC will precipitate in austenite during tandem rolling, at the \(\gamma/\alpha\) interface during transformation, or in supersaturated ferrite during coiling. The short gap-time during tandem rolling and rapid cooling on run-out table will inhibit the precipitation of TiC, so the most part of dissolved Ti precipitated during coiling process. As shown in fig. 4 (a), as the Ti content increases, the dissolved Ti element in matrix also increases gradually. Besides, when the Ti content exceeds 0.042%, the increasing trend becomes more obvious. Because of rapid increase of chemical driving force and dramatic decrease of diffusion velocity of elements at lower transformation temperature, a great number of nanometre-sized TiC precipitated from the ferrite during coiling process, shown in Fig. 4 (c), which play a role of pinning dislocation and improve the precipitation enhancement increment, so the strength of 0.05Ti and 0.07Ti steel increase significantly.

\[
\frac{\text{Ti} - [\text{Ti}]}{\text{N} - [\text{N}]} = 3.4
\]

(10)
Figure 4. (a) Equilibrium solubility of TiN at 1220°C, precipitation of (b) TiN, (c) TiC.

For fine grain strengthening, 0.02Ti, 0.03Ti and 0.04Ti steel have little difference, fine grain strengthening is enhanced in 0.05Ti and 0.07Ti steel. Most of the TiN particles have precipitated during the cooling process of vacuum smelting, because of higher temperature and slow cooling speed, the TiN particles will coarsen, and its inhibition effect on recrystallization is weaker. However, the TiC nucleating in austenite during tandem rolling can inhibit the growth of recrystallized austenite grains effectively. They can also act as nucleation sites to refine grain. In addition, the TiC nucleating at the γ/α interface during transformation can pin the grain and inhibit grain growth. The dissolved Ti element and the theoretical precipitation temperature of TiC of 0.05Ti and 0.07Ti steel are significantly higher than other steels, so more precipitated TiC particles can promote grain refinement.

4. Strength Prediction of C-Mn-Ti Steel

The study on the prediction and control of microstructure-property evolution plays an important role in improving the green and intelligent development of the steel industry. Based on the research on the strengthening mechanism of Ti microalloyed low carbon steel[21], the following model to predict the strength of Ti-containing microalloyed steel was established. In this model, The effect of small amount of bainite on the strength is corrected by the coefficient of the last item.

\[
\begin{align*}
YS &= 37[Mn] + 83[Si] + 59[Al] + 38[Cu] + 11[Mo] + 33[Ni] - 30[Cr] + 680[P] + \sigma_p + 17.4d_{\alpha}^{0.5} + 98.7 \quad (11) \\
TS &= 634.7[C] + 53.6[Mn] + 99.7[Si] + 651.9[P] + 472.6[Ni] + 3339.4[N] + \sigma_p + 11d_{\alpha}^{0.5} + 194.46 \quad (12)
\end{align*}
\]

Where, \(YS\) - yield strength, \(TS\) - tensile strength, MPa; \(d_{\alpha}\) - ferrite grain size, mm; \(\sigma_p\) - precipitation strengthening.

The strength of the representative Ti microalloyed low carbon steel Q345B steel were calculated to verify the accuracy of this model. Fig. 5 shows the prediction results of Q345B steel. According to the results of 198 sets of data, it was found that the relative error of yield strength was within ± 8% and the relative error of tensile strength was within ± 7%. Besides, the average absolute error and standard deviation of the yield strength and tensile strength were small, which ensure the stability of this model.

Figure 5. Strength prediction of Q345B steel.

5. Conclusions

(1) The dynamic recrystallization model of Ti microalloyed low carbon steel has been regressed. It was found that the recrystallization activation energy increases parabolically as the Ti content increases. The solid-solved Ti and precipitated particles could hinder the movement of dislocation and grain boundary,
which inhibit the recrystallization process, so the recrystallization activation energy increases gradually. As the Ti content increases, the inhibition of the recrystallization by the solid-solved Ti and the precipitated particles is offset by the effect of refining initial austenite grain, which makes the recrystallization activation energy increase slowly.

(2) As the Ti content increases, the yield strength, tensile strength and yield ratio increase, while the elongation decreases. When the Ti content exceeds 0.042%, the strength of the test steels increases significantly. Precipitation hardening of nanometre-sized TiC precipitated from the ferrite during coiling process is the main reason.

(3) The calculated yield strength agrees well with the measured value. The fine grain strengthening contributes most to the increment of strength, while the precipitation strengthening is the main reason for the difference of the strength of the test steel.

(4) On the basis of C-Mn steel, the strength prediction model of Ti microalloyed low carbon steel has been developed. In addition, the strength of the representative Ti-containing steel Q345B has been predicted, the relative error of predicted yield strength and tensile strength are within ±8% and ±7% respectively.

Acknowledgments
This work was financially supported by Joint Fund of Iron and Steel Key Project (UI460204), and the State Natural Sciences Foundation of China (U1660117).

References
[1] Shi Z, Chai X, Chai F, et al. The mechanism of intragranular ferrite formed on Ti-rich (Ti,V)(C,N) precipitates in the coarse heat affected zone of a V–N–Ti microalloyed steel. Materials Letters. 2016;175(14):266-270.
[2] Mao X, Chen Q, Zhu D. Recent development of microalloying technology in thin slab casting and rolling process. Iron & Steel. 2008;43(4):1-9.
[3] Mao X, Huo X, Sun X, et al. Strengthening mechanisms of a new 700MPa hot rolled Ti-microalloyed steel produced by compact strip production. Journal of Materials Processing Tech. 2010;210(12):1660-1666.
[4] Eghbali B. Microstructural development in a low carbon Ti-microalloyed steel during deformation within the ferrite region. Materials Science & Engineering A. 2008;480(1–2):84-88.
[5] Du K, Yu Y, Zhang S, et al. Nano-carbide precipitates in Ti microalloyed steel under ultra fast cooling condition and their strengthening effect. Nonferrous Metals Science & Engineering. 2016;7(4):27-32.
[6] Wang C, Yong Q, Sun X, et al. Effects of Ti and Mn contents on the precipitate characteristics and strengthening mechanism in Ti microalloyed steels produced by CSP. Acta Metallurgica Sinica. 2011;47(12):1541-1549.
[7] Kostryzhev AG, Shahrani AA, Zhu C, et al. Effect of deformation temperature on niobium clustering, precipitation and austenite recrystallisation in a Nb–Ti microalloyed steel. Materials Science & Engineering A Structural Materials Properties Microstructure & Processing. 2013;581(581):16-25.
[8] Sellars CM, Tegart WJM. Hot Workability. Metallurgical Reviews. 1972;17(1):1-24.
[9] Sanghyun C, Kang KB, Jonas JJ. The Dynamic, Static and metadynamic recrystallization of a Nb-microalloyed steel. Transactions of the Iron & Steel Institute of Japan. 2001;41(1):63-69.
[10] Zhou, X, Liu Z, Wu D, et al. Determination of model parameters of dynamic recrystallization for Nb bearing steels during flexible thin slab rolling. Acta Metallurgica Sinica. 2008;32(4):1188-1192.
[11] Mao X, Chen Q, Sun X. Metallurgical interpretation on grain refinement and synergistic effect of Mn and Ti in Ti-microalloyed strip produced by TSCR. Journal of Iron and Steel Research, International. 2014;21(1):30-40.
[12] Xu G, Gan X, Ma G, et al. The development of Ti-alloyed high strength microalloy steel. Materials & Design. 2010;31(6):2891-2896.
[13] Li D, Ye Q, Zhou C, et al. Study on precipitation and fine grain strengthening effects of low carbon steel with Nb-Ti. Angang Technology. 2012(4):21-25.

[14] Qu Y. Principles of steelmaking. Beijing (CN): Metallurgical Industry Press; 1994.

[15] Yong Q. Microalloyed steel: physical and mechanics metallurgy. Beijing (CN): Machinery Industry Press; 1989.

[16] Yong Q. The second phase of steel. Beijing (CN): Metallurgical Industry Press; 2006.

[17] Gladman T. Precipitation hardening in metals. Metal Science Journal. 1999;15(1):30-36.

[18] Gladman T. Physical metallurgy of microalloyed steels. London (UK): Maney Publishing; 1997.

[19] Zhang G, Yang S, Jiang K. Influence of precipitation strengthening on yield strength increment $\Delta \sigma_p$ and chemical composition designing of low alloy steel. Journal of Hohai University Changzhou. 2000;14(2): 16-21.

[20] Mao X. Microalloying technology of thin slab continuous casting and rolling. Beijing (CN): Metallurgical Industry Press; 2008.

[21] Hodgson PD, Gibbs RK. A mathematical model to predict the mechanical properties of hot rolled C-Mn and microalloyed steels. Transactions of the Iron & Steel Institute of Japan. 1992;32(12):1329-1338.