A STUDY ON THE RELATION OF RETAINED AUSTENITE TO MECHANICAL PROPERTIES IN COLD ROLLED TRANSFORMATION-INDUCED PLASTICITY STEEL*

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Abstract

A CMnSiAl transformation induced plasticity (TRIP) steel was used to study the effect of retained austenite on room-temperature mechanical properties. The steel plates with retained austenite were obtained by hot rolling, cold rolling and subsequent continuous annealing. The starting and finishing temperature of hot rolling are between Ac1 and Ac3. Reduction ratio of cold rolling is 75%. The continuous annealing is carried out at different intercritical temperatures. The relationship between work hardening exponent and retained austenite was discussed. The results show that, the Ac1 and Ac3 were much high because of the alloy elements, and the temperature range between them was wide. Due to the high hot rolling temperature, the grains was hereditarily refined as a result of dynamic recrystallization. Annealing at intercritical temperature of 930 ºC, retained austenite with relatively high stability reached a maximum volume fraction of 25%, a maximum total elongation of 30.2% and a best ultimate tensile strength × total elongation of 20.1 GPa·%. Instantaneous work hardening exponent reflects strengthening mechanisms at different strain stages. The TRIP effect of retained austenite is the main mechanism during deformation. With retained austenite of sufficient amount and high stability, continuous work hardening was observed in the tensile specimen of 930 ºC.

Keywords: Cold rolling; Continuous annealing; Retained austenite; Mechanical property.

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1 INTRODUCTION

Demands of improving energy utilization efficiency and reducing greenhouse gas emission have been increased. The manufacturing industry is required to produce lightweight automobile as well as improve safety performance. TRIP steel is widely applied to auto parts due to its low cost, good mechanical properties and high energy absorption rate during collision. It can be used to produce thinner automobile sheet and reduce energy consumption. [1, 2] The microstructure of TRIP steel is generally composed of ferrite, bainite, a small amount of martensite, and retained austenite. The metastable austenite transforms into hard martensite during strain process. [3] This phase transformation can increase both strength and ductility. The stability of retained austenite is optimal if the austenite presents film-like or acicular. It is not beneficial to TRIP effect that the stability is excessive or insufficient. [4, 5] Yu et al.'s research [6] shows that retained austenite with smaller grain size and higher carbon content is of more stability. The Retained austenite that can continually provide work hardening is beneficial to improve ductility [7, 8]. According to Zackey et al.'s point [3], carbon enrichment of austenite in cold rolled TRIP steel during continuous annealing can be achieved in three stages: intercritical holding, the following cooling and isothermal bainite soak. The carbon is concentrated from ferrite and "carbon-free" bainite preventing potential losses of carbon in austenite. Generally, cold rolled strip of TRIP steel is followed by a hot dip galvanizing process after annealed [9, 10]. For conventional TRIP steel, Alloy elements such as Si, Mn are easily selective oxidized and the oxidation enriched on the substrate surface that is harmful for wettability [11]. Within proper Al, galvanizing property is improved [12, 13].

In this study, a high Al-low Si steel was studied to explore the effect of volume fraction and stability of retained austenite on room-temperature mechanical properties of cold rolled TRIP steel. After hot rolled between Ac$_1$ and Ac$_3$ and cold rolled with reduction ratio of 75%, the samples were continuous annealed with different intercritical temperatures. Multi-phase steel sheets containing retained austenite of reasonable stability were obtained. The characteristics of retained austenite were investigated and instantaneous work hardening was discussed. The relation of retained austenite to room-temperature mechanical properties and optimum process parameter were obtained.

2 MATERIAL AND METHODS

The experimental TRIP steel was melted in a vacuum induction furnace and its chemical composition is given in Table 1. The rolling and annealing processes are giving in Figure 1. The Ac1 and Ac3 were confirmed to be 720 °C and 1030 °C, respectively, calculated by Thermo-calc. The experimental steel was hot rolled above 1050 °C for optimal dynamic recrystallization [14]. The rolled plate was air cooled to 650 °C before coiling and then cold rolled with reduction ratio of 75%. The cold rolled sheets were continuous annealed with different intercritical temperatures (900 °C, 930 °C and 960 °C). The metallographic samples were mechanical ground and polished before etched with 4% nitric acid alcohol solution. The microstructures were observed with a Zeiss field emission scanning electron microscope (SEM) equipped with electron backscatter diffraction (EBSD) function. The volume fraction and carbon content of retained austenite were detected by X-ray diffraction (XRD). The room-temperature mechanical properties of experimental steel was tested with a 50 kN drawing mill. The tensile rate was 2 mm/min.

Table 1. Chemical composition of the experimental TRIP steel (mass percent)

C	Si	Al	Mn	Ti	P	S	Fe

0.19	0.46	1.69	1.67	0.017	0.004	0.003	Bal.

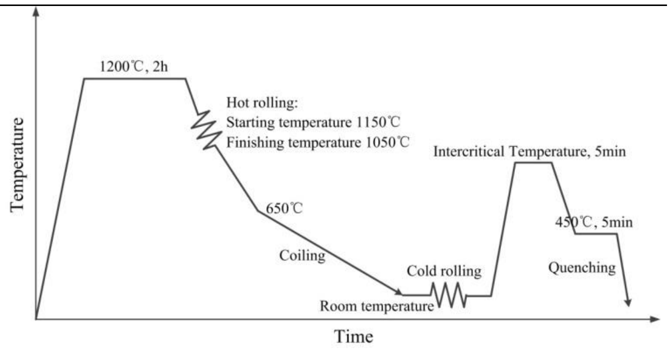

Figure 1. Rolling and annealing procedure

3 RESULTS AND DISCUSSION

3.1 Microstructure after annealing

As seen in Figure 2, the microstructure of experimental steel consisted of ferrite, bainite and retained austenite. When the intercritical temperature was 900 °C (Figure 2 (a)), there was plenty of bainite which present lath or granular. The volume fraction of bainite decreased along with increased temperature, and few bainite was observed at intercritical temperature of 960 °C (Figure 2(c)). The grain size significantly grew at 960 °C that can cause the reduction of strength.

3.2 The characterization of retained austenite

The morphology and distribution of retained austenite was analyzed by EBSD. As shown in Figure 3, the retained austenite mainly reminded along the grain boundary of ferrite while a little ones presented inside ferrite grains. Retained austenite exists as block, granular and film as well. The volume fraction increased first and then decreased. In order to study the TRIP effect, the content of retained austenite and the carbon content in retained austenite were quantitatively detected using XRD.

According to Figure 4, volume fraction and carbon content of retained austenite were obtained [15]. Equation (1) can be used to calculate volume fraction of retained austenite V_γ:

$$V_\gamma = \frac{1.4I_\gamma}{I_\alpha + 1.4I_\gamma} \tag{1}$$

In above equation, I_γ and I_α represent average intensity of diffraction peaks of FCC and BCC, respectively.

Mass fraction of carbon C_γ in retained austenite can be obtained by Equation (2):

$$C_\gamma = \frac{a_\gamma - 3.578}{0.033} \tag{2}$$

where a_γ is lattice constant of FCC.

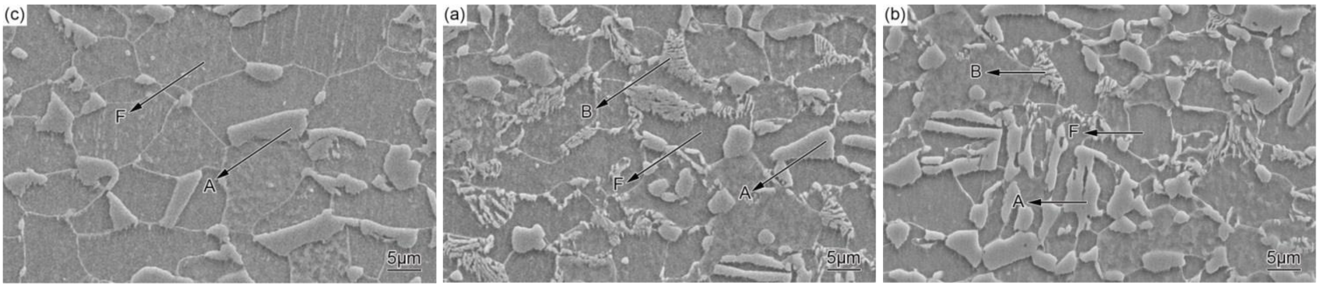

Figure 2 The SEM morphologies of samples at different intercritical temperitures: (a) 900 °C, (b) 930 °C, (c) 960 °C. F, B and A represent ferrite, bainite and austenite, respectively.

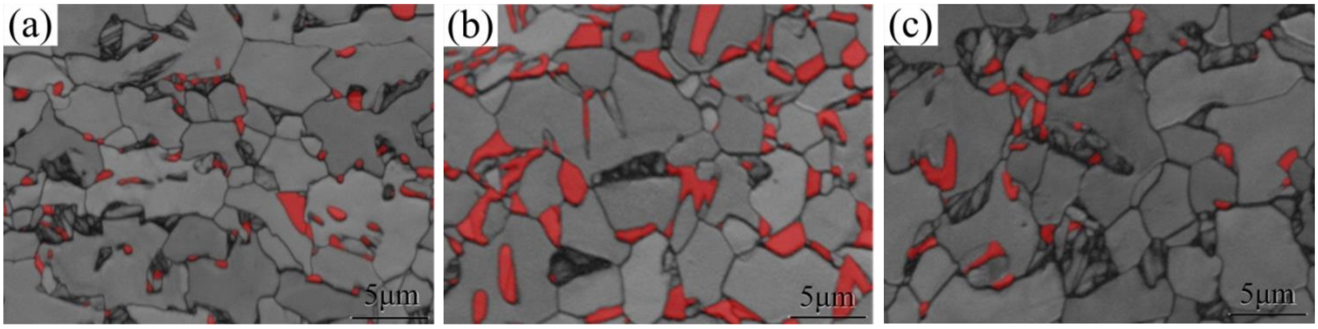

Figure 3 EBSD images of different intercritical temperatures: (a) 900 °C, (b) 930 °C, (c) 960 °C. structure with different gray levels is ferrite, the red part is retained austenite, and the dark part is bainite which was unidentified.

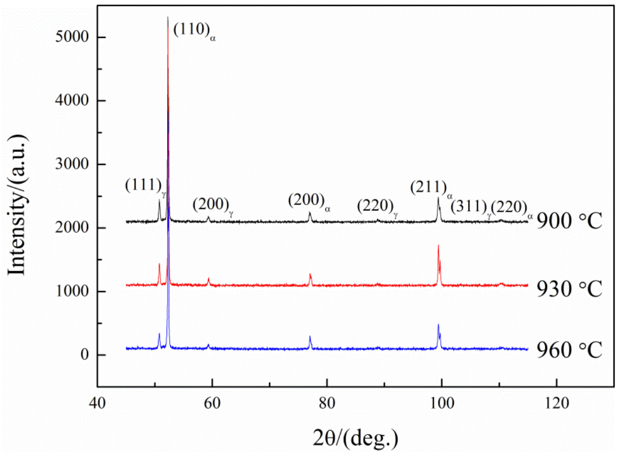

Figure 4 XRD patterns of experimental TRIP steel with different intercritical temperatures

Volume fraction of retained austenite and mass fraction of carbon are given in Table 2. With the increasing intercritical temperature, the volume fraction of retained austenite increases first and then decreases and the mass fraction of carbon in retained austenite decreases while carbon content of 930 °C are close to that of 900 °C. Below a certain intercritical temperature, 930 °C for this TRIP steel, the volume fraction of austenite increased with temperature increasing. When the temperature rose to 930 ° C, volume fraction of high temperature austenite increased. But the carbon content in retained austenite decreased and so did the stability of retained austenite due to lack of ferrite which is the carbon origin of austenite.

Table 2 Volume fraction of retained austenite and Mass fraction of carbon in retained austenite

IT/°C	V_γ/%	C_γ/%
900	23	1.068
930	25	1.061
960	18	0.886

IT represents intercritical temperature.

3.3 Mechanical properties

Figure 5 and Table 3 are tensile experimental curves and mechanical property parameters. The yield strength increases with intercritical temperature increasing. This may be caused by increased carbon content in ferrite due to less carbon concentration to austenite. Then more dislocation in ferrite makes higher yield strength. To improve comprehensive mechanical properties phase transition of retained austenite occurs during tensile test. TRIP effect increases local strength, deforming transfers to other parts, and then necking and appearing of cracks are delayed [16]. In this study, the large volume fraction of retained austenite significantly increased elongation. The samples annealed at intercritical temperature of 930 °C had best ultimate tensile strength × total elongation of 20.1 GPa·%.

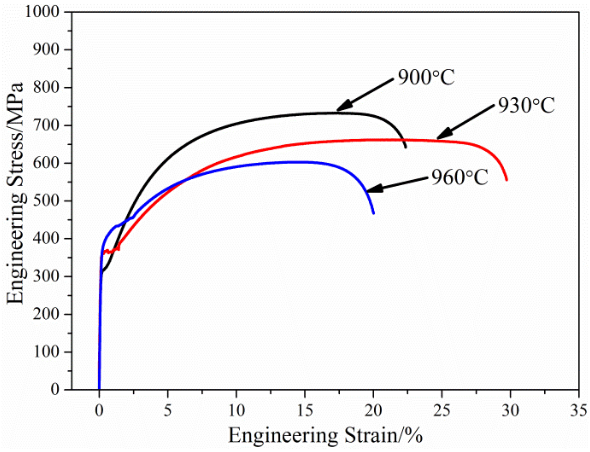

Figure 5 Engineering stress-strain curves of different intercritical temperatures

Table 3 Mechanical properties of samples after annealng

IT/°C	YS/MPa	UTS/MPa	TE/%	UTS×TE/GPa·%
900	288	733	22.5	16.5
930	355	665	30.2	20.1
960	376	622	20.6	12.8

YS, UTS and TE represent yield strength, ultimate tensile strength and total elongation, respectively.

To study ability of plastic deformation and TRIP effect in detail, strain hardening exponent was obtained at different intercritical temperatures. Instantaneous strain hardening exponent n can be obtained by Equation (3) derived from Hollomon formula [17]:

$$n = \frac{d(\ln\sigma)}{d(\ln\varepsilon)} \quad (3)$$

where σ and ε are true stress and true strain, respectively.

According to Figure 6, the curves had two stages: a rapid peak value and a slow decreasing. At the beginning of deformation, the rapid peak value of strain hardening exponent can owe to rapid accumulation of mobile dislocation in ferrite. The second stage is because of TRIP effect. With the continue increasing of strain, the retained austenite can absorb dislocations and transform to hard martensite at the same time which both increase the strength [18]. When strain hardening exponent n is equal to true strain, the necking occurs and material reaches failure stage [19]. As a result, with more retained austenite homogeneous plastic deformation process is prolonged and necking is delayed, so the ductility is improved. The samples with intercritical annealed temperature of 930 °C had most retained austenite. Retained austenite provided sustainable strain hardening, so the samples had optimal comprehensive mechanical properties.

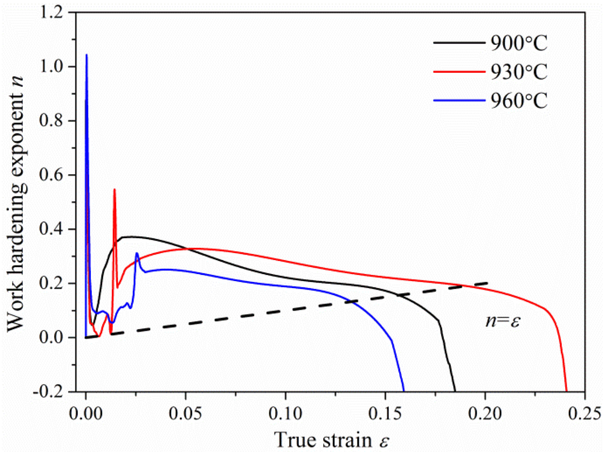

Figure 6 Work hardening exponent curves of different intercritical temperatures

4 CONCLUSION

A cold rolled TRIP steel was continuous annealed at different intercritical temperatures. Microstructure, characterization of retained austenite and mechanical properties were studied, the relationship between retained austenite and work hardening was established. The following are the conclusions:

1) The microstructure of cold rolled sheets consisted of ferrite, bainite and retained austenite. With intercritical temperature increasing, the volume fraction of bainite decreased, the volume fraction of retained austenite increased first and then decreased, and grain size increased.
2) Annealing at intercritical temperature of 930 °C, the volume fraction of retained austenite was 25% and the mass fraction of carbon in retained austenite was 1.061%. Retained austenite with carbon enrichment has well room temperature stability and can provide continuous strain hardening.
3) The comprehensive mechanical properties of 930 °C was confirm to be optimal. The yield strength was 355 MPa, ultimate tensile strength was 665 MPa, and total elongation was 30.2%. The best ultimate tensile strength × total elongation was 20.1 GPa·%.

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