Effect of Heat Treatment on Formability in 0.15C-1.5Si-1.5Mn Multiphase Cold-Rolled Steel Sheet

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The effects of volume fraction and the stability of retained austenite on the formability of a 0.15C-1.5Si-1.5Mn (hereafter all in wt.%) TRIP-aided multiphase cold-rolled steel sheet were investigated after various heat treatments. The steel sheets were intercritically annealed at 800°C, and isothermally treated at 400°C and 430°C. Microstructural observation, tensile tests and limiting dome height (LDH) tests were conducted on the heat-treated sheet specimens, and the changes in retained austenite volume fraction as a function of tensile strain were measured using an X-ray diffractometer. The results showed a plausible relationship between formability and retained austenite stability. Although the same amount of retained austenite was obtained after isothermal holding at different temperatures, better formability was obtained in the specimens with the higher stability of retained austenite. If the stability of the retained austenite is high, the strain-induced transformation of retained austenite to martensite can be stably progressed, resulting in a delay of necking to the high strain region and improvement in formability.

Keywords : multi-phase cold-rolled steel sheet, TRIP, retained austenite, stability, formability

1. INTRODUCTION

Reduction in the weight of automobile bodies has been continuously needed in order to improve fuel efficiency and reduce the amount of emission gas for better environmental preservation. These efforts have led to rapidly rising demands for high-strength cold-rolled steel sheets with excellent formability [1]. In response to this trend, C-Si-Mn TRIP (transformation induced plasticity)-aided cold-rolled steel sheets whose microstructures are composed of ferrite, bainite, and retained austenite, have been developed [2-5]. Since they have at once both high strength and elongation because of the martensitic transformation of retained austenite during plastic deformation, they have been receiving increased attention as new high-formability cold-rolled steel sheets for automobile bodies. Studies on currently available C-Si-Mn TRIP-aided cold-rolled steel sheets reveal that most research has been mainly undertaken in the carbon content range from 0.2 to 0.4 wt.% in order to achieve a high amount of retained austenite by studying the effect of heat treatment [6,7], alloying elements [2,8,9], the transformation kinetics of retained austenite during deformation [10,11], and the deformation temperature of TRIP behavior [12,13].

Using a stretch forming test, Matsumura et al. [6] confirmed that the press formability of multiphase steel sheets could be improved owing to the merits of their TRIP effect, and that the initial volume fraction of retained austenite and the deformation induced transformation rate were the most important factors determining formability. Hiwatashi et al. [7] reported that TRIP-aided multiphase steel sheets were found to have very good stretchability near the plane-strain state and to yield high and deep drawability in the limiting dome height test. Since deformation on the punch shoulder occurs in the plane-strain state, the TRIP effect increases the fracture strength, thereby improving the deep drawability of the steel. However, despite the generally accepted knowledge of the excellent formability of TRIP-aided multiphase steel sheets due to the high strength and elongation, studies on the effect of heat treatment conditions on formability have been quite limited.

Thus, in the present study, a 0.15C-1.5Si-1.5Mn TRIP-aided multiphase cold-rolled steel sheet having lower carbon content than conventional TRIP-aided steel sheets was adopted to study the effect of heat treatment on formability. Based on the results
of both former studies [14,15] and present findings, the effect of the volume fractions and stability of retained austenite on mechanical properties and formability were investigated.

2. EXPERIMENTAL PROCEDURES

2.1. Preparation of cold-rolled steel sheet
A 0.15C-1.5Si-1.5Mn steel ingot was fabricated with vacuum induction melting and aluminum-killing. Table 1 lists its chemical composition, together with the AC1, AC3, and martensite start (Ms) temperatures calculated from Andrew’s equation [16]. The steel ingot was rough-rolled into a slab 25 mm in thickness. The slab was homogenized at 1250°C for 2 hr and hot-rolled into sheets 3 mm in thickness. The hot-rolled steel sheet was pickled by a 10% HCl solution of 80°C, and was cold-rolled into sheets 0.8 mm in thickness.

Intercritical annealing was conducted for 5 min at 800°C where the volume fraction ratios of ferrite and austenite are about 50:50. Then, isothermal treatment was carried out for 3 min at 400°C (named as ECO-A) and at 430°C (named as ECO-B) followed by air cooling.

2.2. Microstructural observation and tensile test
The heat-treated specimens were etched in a 10% sodium metabisulfite solution (Na2S2O3·H2O 10 g+H2O 100 ml), and observed with an optical microscope. Mechanical properties were evaluated by conducting tensile tests on tensile specimens (longitudinal direction) with a gauge length of 25 mm and a width of 6.3 mm. The tensile specimens were deformed at room temperature at a crosshead speed of 2.5 mm/min. using a tensile tester. The engineering stress-strain curves obtained from the tensile test were converted to true stress-true strain curves to determine the strain hardening exponent, $n$, in the uniform strain range from 5 to 20%. After the tensile specimens were deformed at angles of 0°, 45°, and 90° from the rolling direction were deformed at 15%, the length and width of the gauge section before and after the deformation were measured to obtain the plastic strain ratio, $r$.

$$ r = \epsilon_f / \epsilon_p = \ln(w_f / w_0) / \ln(t_f / t_0) $$

Here, $w$ and $t$ refer to the width and the thickness of the gauge section, respectively, while the subscripts 0 and f refer to pre- and post-deformation, respectively.

2.3. Measurement of volume fraction and stability of retained austenite
Changes in volume fraction of retrained austenite vs tensile strain were measured using an X-ray diffractometer (XRD). An Mo-Kα characteristic ray was used, and the volume fraction of retained austenite, $V_γ$, was calculated from the integrated intensity of the ferrite and austenite peaks using the following equation [17],

$$ V_γ = 1.4I_γ /(I_α + 1.4I_γ) $$

where $I_γ$ is the average integrated intensity obtained at the (220)$_γ$ and (311)$_γ$ peaks, and $I_α$ is that obtained at the (211)$_α$ peak.

To evaluate the stability of retained austenite as a function of heat-treatment, the strain-induced martensitic transformation rate formula, recently suggested by Chung [10] and Chang et al. [11], was applied.

$$ \log (\ln f_s / (f_s - f)) = \log \kappa + m \log \epsilon $$

Here, $f_s$ and $f$ refer to the saturated martensite volume fraction and the martensite volume fraction transformed during deformation, respectively, while $\epsilon$ and $m$ refer to the true strain and the deformation mode coefficient, respectively. $\kappa$ is defined as the stability coefficient of retained austenite, and the larger $\kappa$ value indicates the lower stability of retained austenite and the faster martensitic transformation.

2.4. Evaluation of formability
To evaluate the stretch formability of the cold-rolled steel sheet specimens as a function of heat-treatment, limiting dome height (LDH) tests were conducted using a hemispheric punch. A schematic diagram of the LDH test is given in Fig. 1. The minimum limiting dome height, $LDH_0$, was obtained from 180-mm-long rectangular specimens of varying width. The rectangular specimens were marked on the surface with

![Fig. 1. Schematic diagram of the limiting dome height (LDH) test.](image-url)