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Warm tensile properties of low-alloy TRIP steel warm-rolled just prior to isothermal holding treatment

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Abstract. Low-alloy TRIP steel sheets with ultra-high-strength that utilize transformation-induced plasticity of retained austenite have high strength and ductility. In this study, low-alloy TRIP steel sheets with thermo-mechanical treatment with warm rolling were prepared, and the effects of warm rolling on tensile properties were investigated. A hot-rolled sheet of the steel with Ms of 418.5°C was austenized and then quenched in a salt bath kept at 450°C. Two specimens of the sheet were warm-rolled by 40 and 60% and then isothermally held at 350°C for 1ks. For comparison, a specimen was directly isothermally heat-treated at 350°C for 1ks. The three specimens were subjected to microstructural characterizations and tensile tests at temperatures ranging from 25 to 300°C. It was confirmed that the warm rolling increases the ductility/strength balance. The X-ray diffraction showed that the warm rolling causes an increase in volume fraction of the retained austenite, while its stability against the tensile deformation was somewhat complicated. The effect of the temperature and rolling reduction on the uniform elongation, which is the parameter mostly affected by TRIP, was successfully understood in terms of the volume fraction and the stability of the retained austenite.

Introduction

Low-alloy TRIP steel sheets, which are ultra-high strength steel sheets utilizing transformation-induced plasticity of retained austenite, are attracting attention as automotive steel sheets that contribute to carbon neutrality due to their high strength and high ductility. Low-alloy TRIP steel sheet is known to exhibit high ductility at room temperature, and it has been reported that high ductility is also exhibited during warm deformation by controlling stress or strain-induced transformation of retained austenite [1]. Previous studies [2-6] have reported the properties of low-alloy TRIP steels prepared by heat treatment only, and there are no reports on the warm tensile properties of low-alloy TRIP steels subjected to thermos-mechanical treatment.

In this study, low-alloy TRIP steel sheet specimens were fabricated by thermo-mechanical treatment including warm rolling and their tensile properties were assessed at temperatures ranging from 25 to 300°C. Then discussion on the effect of warm rolling was made based on the

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experimental evaluation of the volume fraction of the retained austenite and its stability against the tensile deformation.

Table 1 Chemical composition of the sample in mass %.

C	Si	Mn	Nb	Mo	Al	Fe
0.20	1.50	1.50	0.050	0.20	<0.005	Bal.

Experimental procedure

Form a hot-rolled steel sheet of 5 mm thickness with a chemical composition shown in Table 1 (Ms: 418.5°C), three specimens of 1, 1.67 and 2.5 mm thickness were cut out. The latter two specimens were thermo-mechanically treated as shown in Fig. 1, i.e., austenized in a salt bath at 950°C for 1.2 ks, rapidly cooled to 450°C, below the A_1 temperature, warm-rolled with reductions of 40 and 60%, respectively, to get the same final thickness of 1 mm, iso-thermally heat-treated in a salt bath at 350°C for 1 ks, and finally oil-quenched to room temperature. For comparison, the other specimen of 1 mm thickness was austenized and rapidly cooled to 450°C in the same way as above, and then iso-thermally heat-treated at 350°C for 1 ks without warm rolling (0% reduction).

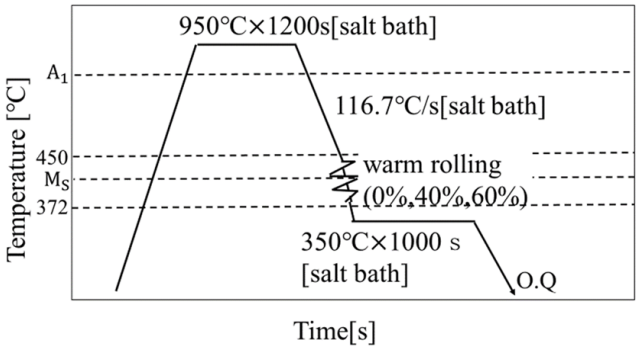

Fig. 1 Schematic of thermo-mechanical processing used in this study.

Tensile-test pieces with a gauge length of 6 mm and width of 3 mm were cut out of the thermo-mechanically treated sheets of the thickness of 1 mm with three reductions (0, 40 and 60%). Tensile tests were conducted using a screw-driven testing machine (Shimadzu AG-G) with an electric furnace at a crosshead speed of 1.0 mm/min at temperatures of 25, 200 and 300°C. Tests were started 300 s after the target specimen temperature was reached. Two tests were carried out for each condition.

To observe the microstructure after the thermo-mechanical treatment, the specimens were wet-ground up to #2000 grit, buffed to a mirror finish, and etched with a nital reagent (ethanol with 5% nitric acid). Microstructural observation and fracture surface observation after the tensile tests were conducted using a scanning electron microscope (SEM, Hitachi S-3400N).

To assess the amount of retained austenite in the three specimens with warm reduction of 0, 40 and 60%, 10 mm square test pieces were cut, electropolished to remove the surface deformed layer , and subjected to X-ray five-peak diffraction method using X-ray diffractometer (Rigaku Ultima IV) with Cu-Kα radiation. The retained austenite volume fraction was determined from the obtained measurement results by combining the diffraction planes, and the average of these values was used as the final retained austenite volume fraction.

Using the k value defined by eq. (1), stability of the retained austenite against tensile deformation was evaluated.

$$k = \frac{\log f_{r0} - \log f_r}{\varepsilon} \quad , \tag{1}$$

where f_{r0}, f_r and ε are volume fractions of retained austenite before and after the tensile deformation and tensile true strain, respectively. Lower k value means higher stability of the retained austenite. To measure the f_{r0} and f_r, samples were cut out from grip portion and portion adjacent to the fracture point, respectively, after the tensile test, while was estimated from thickness and the width before and after the test at the latter portion.

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Results and discussion

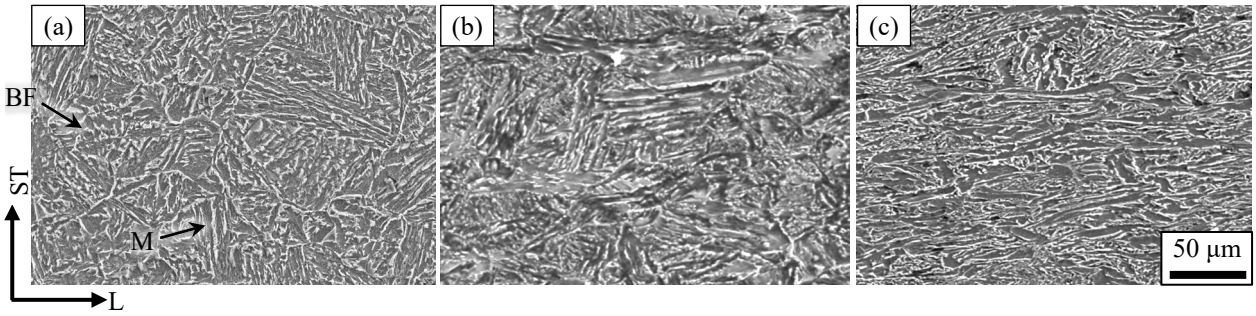

Fig. 2 Microstructures of the three specimens. (a) 0%, (b) 40%, (c) 60%.

Microstructures of the three specimens subjected to the thermo-mechanical processing are shown in Figs. 2 (a) to 2(c). The microstructures of all the three specimens are composed of bainitic ferrite and martensite, examples of which are indicated by labels of BF and M, respectively, and they come to elongate along the rolling direction as the rolling reduction increases. As will be mentioned later, retained austenite should be present but not visible in these images.

Figures 3(a) to 3(c) show stress-strain curves of the three specimens tested at 25, 200 and 300°C, while Figures 4(a) to 4(e) show five mechanical properties obtained from the tests. From these figures, it is clear that warm rolling increases the strength at all the temperatures and this effect is higher in the reduction of 40% than 60%. The effect of warm rolling on the ductility is somewhat complicated: ductility is decreased by 40% rolling but increased by 60% rolling. Temperature dependency of the product of ultimate tensile strength (σ_U) with total elongation (ε_T) is demonstrated in Fig. 4(e) as a measure of toughness and the balance of strength with ductility. In terms of the $\sigma_U \times \varepsilon_T$ value or the balance between strength and ductility, the relationship between unrolled and 40% rolled specimens seems to be normal, which can be frequently seen in many metallic materials: the higher the strength, the lower the ductility. This tendency is seen in Fig. 4(e): almost the same values of $\sigma_U \times \varepsilon_T$ for the 40% rolled and unrolled

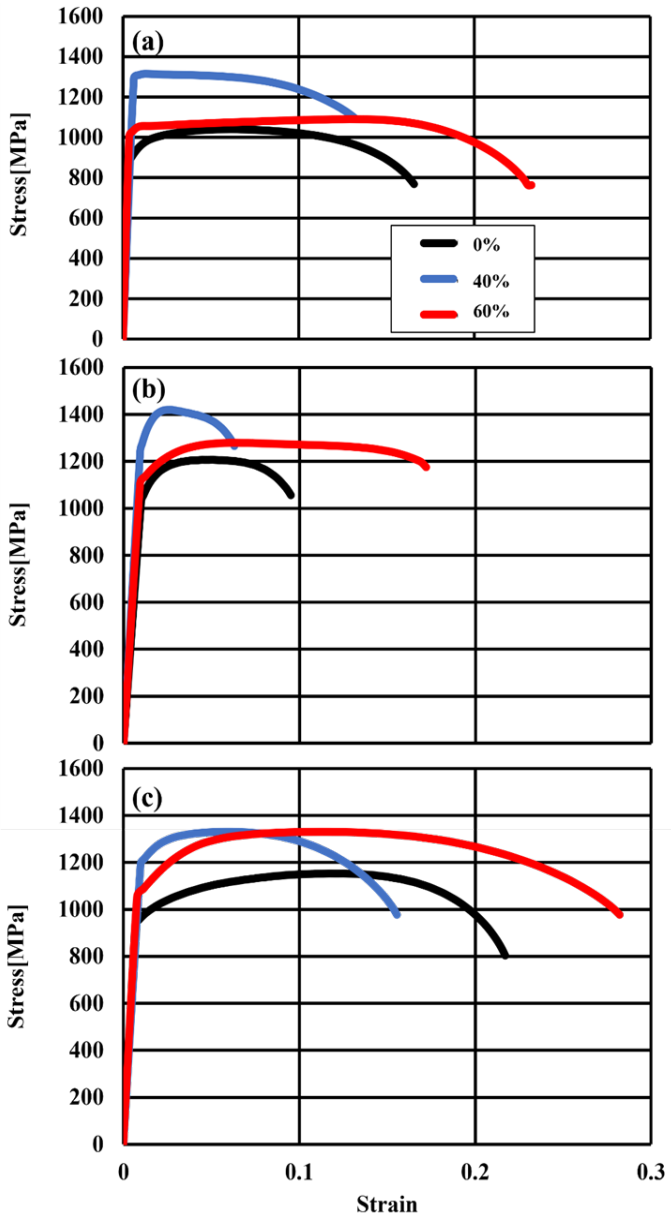

Fig. 3 Stress-strain curves of the three specimens tested at 25°C (a), 200°C (b) and 300°C (c).

specimens at all the temperatures. In contrast, the 60% rolled specimen shows both higher strength and higher ductility than unrolled specimen at all the temperatures.

The higher strength and ductility of the 60% rolled specimen will be discussed here. The uniform elongation, ε_U, is the parameter most affected by TRIP [2,7] since the martensite newly formed by the local deformation causes strain hardening, leading to diffusion of the local necking. In Fig. 4(c), ε_U of the 60% rolled specimen is higher than that of the unrolled specimen but the difference decreases as the temperature increases, resulting in almost the same values at 300°C for the two specimens. The cause of this phenomenon will be discussed further in terms of the amount and stability of retained austenite.

Figures 5(a) and 5(b) show temperature dependency of f_{r0} and k. It is obvious that f_{r0} increases with increasing rolling reduction. This can be attributed to the refinement of the microstructure, probably dislocation cell size, by warm rolling, which causes an increase in the number density of the nucleation sites for martensite, resulting in the increase in the number density of film-like retained austenite that forms on the periphery of the martensite. Another probable cause for the increase in f_{r0} with increasing rolling reduction is a decrease in the cooling rate from the austenization temperature to the isothermal holding temperature caused by adding the warm rolling process. According to the previous study [3], a decrease in the cooling rate promotes the refinement of the matrix microstructure in a block, leading to the same effect as above. The higher f_{r0} indicates the larger potential capability to exert the TRIP effect that enhances the strain hardening during tensile deformation, leading to larger uniform elongation. However, lower stability of the austenite, higher k value, is also needed for the TRIP to actually take place. From Fig. 5(b), k value of the 60% rolled specimen is higher than the other two specimens at 25°C, but it decreases with increasing temperature, and becomes lower at 300°C. Thus, it can be deduced that the higher ε_U value of the 60% rolled specimen than unrolled specimen at 25°C was caused both by the higher f_{r0} and k values, while the effect of the higher f_{r0} was alleviated by the lower k at 300°C.

Next, the cause of the change of k value with temperature will be discussed. Sugimoto et al. [4] proposed that a trough should appear in the k value vs. temperature curve when strain-induced martensite transformation (SIMT) becomes stagnant and strain-

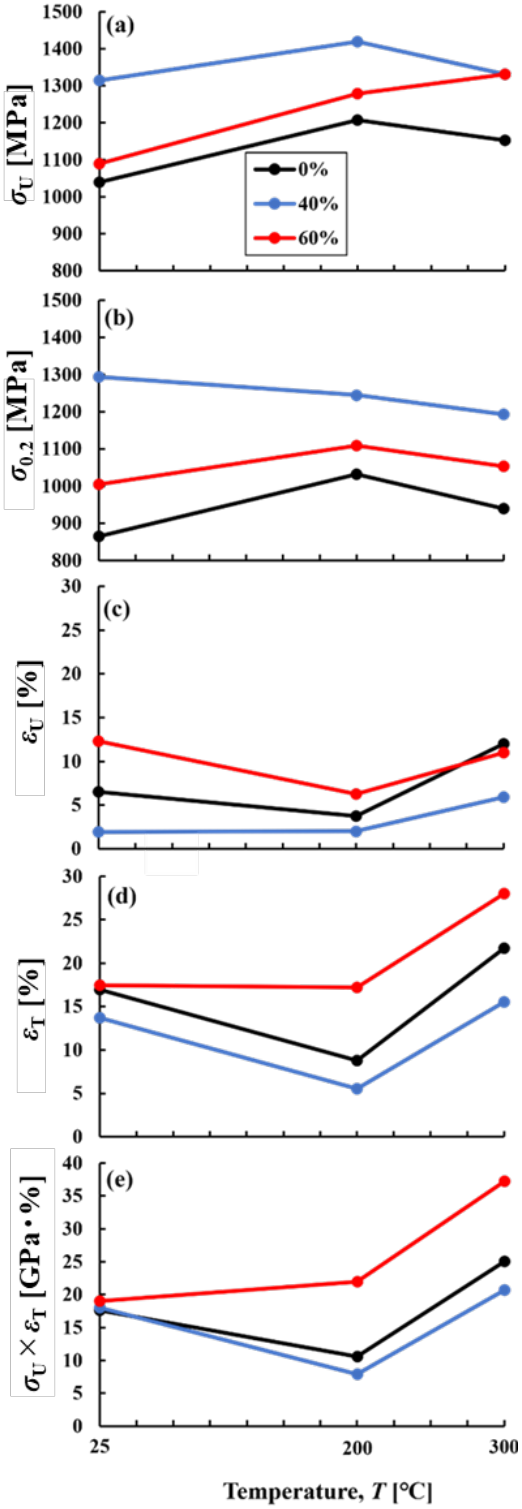

Fig. 4 Temperature dependence of mechanical properties for each specimen. (a) ultimate tensile strength (σ_U), (b) 0.2% proof stress ($\sigma_{0.2}$), (c) uniform elongation (ε_U), (d) total elongation (ε_T), (e) $\sigma_U \times \varepsilon_T$.

induced bainitic transformation (SIBT) starts but not abundantly: SIMT occurs at a lower temperature range while SIBT at a higher temperature range. They suggested that the trough temperature corresponds to the temperature where the ductility becomes maximum. In the present study, from Fig. 5(b), the trough of k values seem to be present at around 25°C and over 300°C for unrolled and 60% rolled specimens, respectively. Therefore, the temperature range for SIMT has been spread toward higher temperature side in 60% rolled specimen compared to the unrolled specimen.

Finally, the cause for the shift of the k-trough temperature in the rolled specimens will be discussed. As shown in Fig. 5(a), f_{r0} increases with rolling reduction, resulting in the decrease of carbon concentration in the retained austenite, which will then raise Ms and Bs temperatures for the retained austenite [8-11]. Hence, the transition temperature from SIMT to SIBT (trough temperature in k value) is deduced to be raised by the rolling.

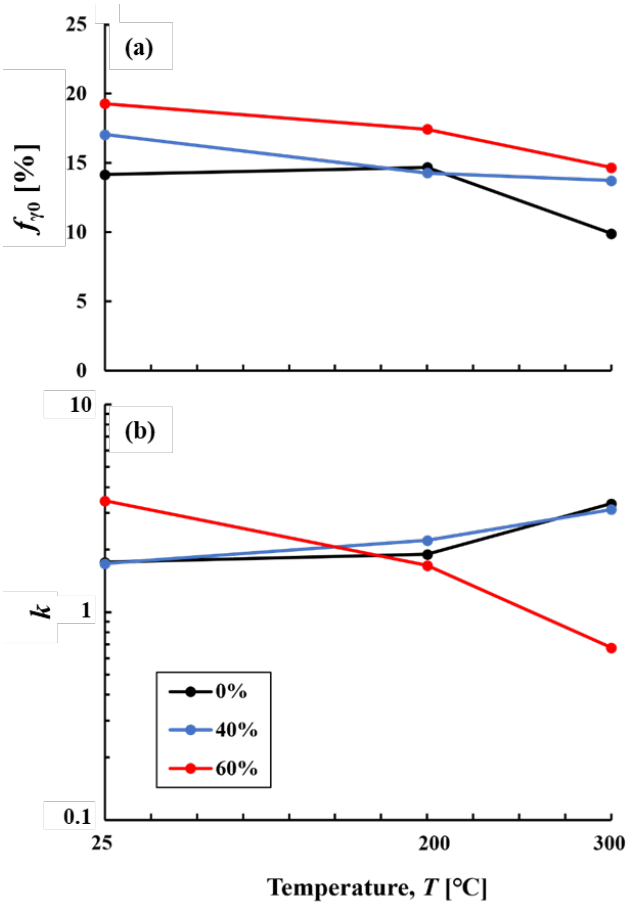

Fig. 5 Temperature dependence of f_r (a) and k valueu (b).

Summary

Tensile properties of a low-alloy TRIP steel affected by warm-rolling prior to isothermal holding treatment were investigated, and the results were discussed in terms of volume fraction of retained austenite and its stability against tensile deformation. It was confirmed that the strength/ductility balance was almost the same at the reduction of 40% and that it was significantly increased by the 60% warm rolling. The latter phenomenon was attributed to the increase in the volume fraction of the retained austenite with the rolling reduction as well as the stability of the retained austenite against the tensile deformation.

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