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Dual phase structure formed by partial reversion of cold-deformed martensite

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ABSTRACT

Effect of prior deformation and heating rate on the dual phase (DP) structure formed by partial reversion of cold-rolled martensite was investigated in a low carbon steel (0.15%C–1.0%Mn). The steel plate was quenched after austenitization to obtain full martensitic structure and then cold-rolled with varying reductions. The cold-rolled specimens were continuously heated at a slow (0.083 K/s) or fast (100 K/s) heating rate up to a temperature above A_1 point to partially form reversed austenite. Increasing rolling reduction rate or lowering heating rate enhanced recrystallization on heating before the onset of reversion, while the undeformed martensite never caused recrystallization irrespective of heating rate. The matrix of DP structure was changed from tempered martensite to equiaxed ferrite through the recrystallization, which resulted in a large difference in the distribution of fresh martensite (reversed austenite). Tensile testing revealed that the excellent strength-elongation balance was obtained in the DP steel produced from undeformed martensite, while higher strength was realized in the steel with prior deformation. With increasing the rolling reduction and the heating rates, the grain size of recrystallized ferrite becomes finer and the tensile strength is more increased. It was also suggested that the competition between recrystallization and reversion during continuous heating could be predicted by the modified tempering parameter.

1. Introduction

Low carbon dual phase (DP) steel composed of ferritic and martensitic structures is widely used for automotive steel sheet because of its excellent mechanical properties, such as high strength, low yield ratio and good deformability. Recently, further strengthening is required in DP steel to reduce the weight and improve the crashworthiness of car bodies. It is already known that grain refinement of ferrite matrix is an effective method to strengthen DP steel without a significant loss of elongation [1–8]. Regarding the grain refinement strengthening of DP steel, some researchers pointed out the importance of the uniform distribution of fine martensite grains to maintain a sufficient elongation [7,8]; by distributing martensite grains finely, the strain localization at ferrite/martensite interface is reduced, and this results in a prevention of void formation. However, when DP steel is produced by cold rolling and annealing process starting from ferrite and pearlite structure, it is inevitable that some coarse martensite islands ununiformly form within ferrite matrix structure because the pearlite region acts as a preferential nucleation site of such a coarse austenite grain. In order to obtain a fine-grained uniform DP structure, a single phase structure without any second phase would be appropriate as a starting structure to distribute fine martensite grains. Ueji et al. focused on the possibility of as-quenched martensite as a starting structure for thermomechanical treatment of steel and succeeded to form an ultrafine grained structure composed of ferrite and nano-cementite particles by annealing of cold-rolled martensite [9]. Similarly, it is thought that martensite would have also a potential as a starting structure to form fine-grained DP structure. In this study, DP structure formed by partial reversion[2] of cold-deformed martensite and its tensile property were investigated in a low carbon steel. In particular, the effect of rolling reduction and heating rates on the formation of DP structure was discussed by taking into account the competition between recrystallization and reversion on heating.

2. Experimental procedure

A low carbon steel with a chemical composition of 0.15%C–1.0%Mn (mass%) was used in this study. This steel

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[2] The heat treatment at (ferrite + austenite) two phase region is referred to as "partial reversion" in this article to emphasize the phenomenon of phase transformation, although it is generally called as "intercritical annealing".

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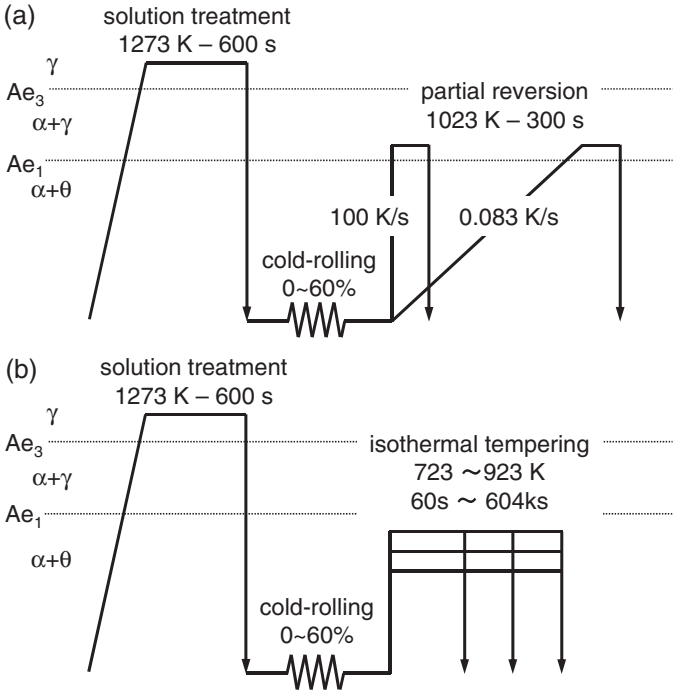

Fig. 1. Heat treatment routes for (a) formation of DP structure and (b) investigation of recrystallization start condition.

was water-quenched after solution treatment in the austenite single phase region in order to obtain a full martensitic structure, and then cold-rolled at a reduction of 0, 20, 40 or 60% in thickness. The cold-rolled materials were heated up to 1023 K at two different heating rates of 0.083 and 100 K/s and held at this temperature for 300 s, followed by water-quenching. Since the holding temperature is higher than the equilibrium reversion temperature: Ae_1 (976 K), austenite partially forms within the matrix during heating or holding stages, and then finally transforms to martensite (fresh martensite) on water-quenching. Additionally, the cold-rolled material was isothermally tempered at 723–923 K for various periods to quantify the recrystallization start condition as a function of tempering parameter. These respective heat treatment routes were displayed in Fig. 1(a) and (b). The microstructure was observed from the transverse direction of the cold rolling process with an optical microscope for the specimens etched by 3% Nital or LePera (1% sodium disulfite:4% picric acid alcohol = 1:1) etchant. The volume fraction of fresh martensite was measured by digital binary-code image obtained from the optical micrograph. Crystallographic orientation imaging map was obtained by means of electron backscatter diffraction method using the scanning electron microscopy. Reversion temperature on continuous heating: Ac_1 was measured using a thermal dilatation tester equipped with a temperature control system. The dilatation tests were performed for the test pieces of $10^{l} \times 3^{w} \times 3^{t}$ mm in dimension. Tensile testing was carried out at an initial strain rate of $5.6 \times 10^{-4}\,s^{-1}$ for plate test pieces with a gauge size of $6^{l} \times 3^{w} \times 1^{t}$ mm.

3. Results and discussions

3.1. Effect of cold-rolling reduction and heating rates on DP structure

Fig. 2 shows optical micrographs of (a) 0, (b) 20, (c) 40 and (d) 60% deformed materials before partial reversion. The initial material (a) has full lath martensitic structure consisting of packets and blocks, and its average prior austenite grain size was less than 100 μm. Micrographs of 20, 40 and 60% deformed materials (b, c, d) reveal that the martensitic structure is plastically deformed and gradually elongated along rolling direction (RD). Fig. 3 represents optical micrographs of DP structure formed by partial reversion of cold-rolled martensite under different conditions of rolling reduction and heating rates. In these micrographs, the white and gray etched regions correspond to fresh martensite and unreversed matrix, respectively. All specimens have DP structure containing fresh martensite grains and its volume fraction was almost the same at approximately 30%. Since the value is equal to the thermal equilibrium austenite phase fraction at 1023 K calculated by thermodynamic software (*Thermo-calc. TCFE6*), it is understood that partial reversion had completely finished and an equilibrium state of (ferrite + austenite) was achieved before water-quenching in all specimens. The DP structure exhibits nearly equiaxed microstructure even in the specimens which had been heavily cold-rolled (g, h), and tends to become finer with increasing the both of rolling reduction and heating rates. In the finest DP structure (g), fine fresh martensite grains are uniformly distributed within the matrix with 5.2 μm in average grain size. However, the morphology and distribution of fresh martensite grains were different obviously among specimens and roughly divided into two types as drawn by the broken line. Acicular fresh martensite grains seem to be isolated within the matrix in (a–c), while granular ones form at grain boundaries in the matrix and produce a chain-networked structure in (d–g). Fig. 4(a–d) depicts the inverse pole figure maps of bcc phase in DP structure corresponding to Fig. 3(b–e), respectively. It is more difficult to index crystal orientation of fresh martensite rather than that of unreversed matrix due to its high density lattice defects. Therefore, an existence of fresh martensite is regarded as black colored no data region when the data with confidence index value less than 0.1 are removed, although both of fresh martensite and matrix in DP structure are bcc. It is found from maps (a, b) that tempered lath martensitic structure is remained as matrix of DP structure and acicular fresh martensite grains are preferentially located at the lath and block boundaries. This is typical of austenite nucleation behavior within lath martensite by partial reversion at low temperature in two phase region [10,11]. On the other hand, maps (c, d) clearly indicate that fresh martensite grains surround each ferrite grain without any substructure, which means that cold-deformed martensite had completely recrystallized to ferrite and then reversed austenite nucleated at the ferrite grain boundary with the formation of chain-networked structure. The effect of recrystallization of martensite on the distribution of reversed austenite is schematically illustrated in Fig. 5. Increasing rolling reduction rate or lowering heating rate enhances recrystallization of lath martensitic matrix on heating before the onset of reversion, which has a large influence on the distribution of fresh martensite. The DP structure with recrystallized ferrite matrix (b) becomes finer with increasing both of rolling reduction and heating rates, because the heavier prior deformation leads to the finer recrystallized ferrite structure and its grain growth is suppressed by shortening the time until austenite nucleation stars. However, the recrystallization has never occurred in undeformed martensite. Authors had already investigated the recrystallization of lath martensite and concluded that lath martensite is hardly recrystallized because lath martensitic structure has few nucleation sites for recrystallization characterized by high angle boundary, although the dislocation density is quite high [12,13].

3.2. Prediction of competition between reversion and recrystallization of cold-rolled martensite

It is important to predict the recrystallization behavior and microstructure development on the continuous heating process in the cold-deformed martensite, because the distribution of fresh