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Effect of austenite deformation in non-recrystallization region on microstructure development in low-silicon content TRIP-assisted steels

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ABSTRACT

The influence of austenite deformation in non-recrystallization region on microstructural development in low-silicon content TRIP-assisted steels was investigated. Laboratory simulation of a typical thermo-mechanical control processing was carried out in an automated hot-compression testing machine. Specimens subjected to a typical multi-stage isothermal deformation/cooling program were deformed to true strains of 0, −0.15, −0.25 and −0.35 at various temperatures in austenite non-recrystallization region. Mössbauer spectroscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM) and a novel tint-etching method were used to investigate the microstructure of deformed specimens. The results indicated that the maximum volume fraction (V_{RA}) and carbon content (C_{RA}%) of retained austenite can be obtained by deforming samples to some intermediate strains ($\varepsilon=-0.15$ for V_{RA} and $\varepsilon=-0.25$ for C_{RA}%). However, further straining of samples to $\varepsilon=-0.35$ resulted in a drastic reduction of both parameters due to formation of pearlite. It was found that a decrease in deformation temperature resulted in increasing V_{RA} and C_{RA}%. Moreover, deformation of austenite was associated with morphology changes in retained austenite particles from interlath film-like type in undeformed specimens to blocky and encapsulated types in the deformed specimens.

1. Introduction

Previous studies have emphasized the beneficial effects of ferrite grain refinement on increasing volume fraction and stability of retained austenite in conventional high-silicon and more recently-developed low-silicon content TRIP-assisted steels [1,2]. Ferrite grain refinement is mainly achieved through that of γ grain structure, however, there is a limit in attaining α-grain refinement through γ→α transformation where α is produced from recrystallized, strain-free γ. This limit can be broken if α transforms from deformed γ [3]. The full use of this effect has been made possible in thermomechanical-control processes (TMP) through precise controlling of cooling and deformation cycles. A typical TMP program consists of three stages: (1) deformation in γ-recrystallization region, (2) deformation in non-recrystallization region, and (3) deformation in α+γ (intercritical) region. Microstructural changes caused by each stage can be summarized as follows: stage 1: coarse γ grains refined by repeated deformation and recrystallization, stage 2: formation of deformation bands and intragranular lattice defects in elongated unrecrystallized γ, stage 3: continuation of stage 2 as well as formation of subgrains within deformed α grains.

A systematic study of the transformational characteristics of conventional high silicon content TRIP-aided steels after thermo-mechanical processing has been carried out by Zarei-Hanzaki et al. [4]. As a part of their research, the effect of deformation in non-recrystallization region on the state of retained austenite (RA) has been investigated. They have found that a decrease in deformation temperature increases fraction of RA in final microstructure [5]. This behavior was attributed to the slower kinetics of restoration processes taking place at lower deformation temperatures leading to more strain energy being accumulated in microstructure. According to their studies, the fraction of RA reaches to a maximum level at an intermediate strain and, after a plateau, decreases. The initial increase in the fraction of RA with straining was ascribed to a number of factors such as increasing the amount of strain energy accumulated, development of subgrains in α grains, and increasing the density of ferrite nucleation sites. The subsequent reduction of RA fraction at higher amount of strains was also attributed to the pearlite formation at serrated γ-grain boundaries induced by deformation.

Previous studies carried out on cold rolled low- and high-silicon content TRIP steels which were produced through two-stage heat

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Table 1
Chemical composition under investigation.

Element	C	Mn	Si	Ni	Mo	Al	P,S	N, (ppm)
Weight percent	0.10	1.60	0.60	0.50	0.25	0.025	<0.01	30–40

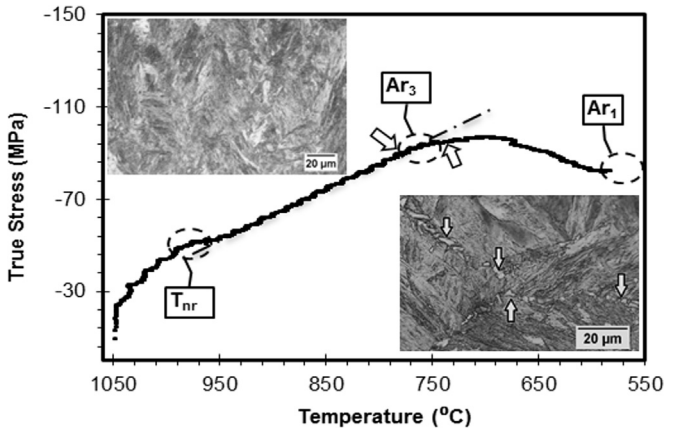

Fig. 1. The CCC true stress–temperature curve of the steel under investigation. The micrographs show the microstructures of samples upon interrupted quenching at temperatures immediately below and above Ar_3.

treatment intercritical annealing and bainitic holding have shown different transformational behaviors between these two type of steels in terms of kinetic of bainite reaction, cementite precipitation, etc. [6]. Therefore, the results obtained from high-silicon TRIP steels after TMP process [1,5,7,8] cannot be utilized to explain the transformational behavior of low-silicon ones. Moreover, only few studies have been carried out on the latter type of steels [9–12]. The present study is, thus, aiming at investigating the influence of applying deformation at non-recrystallization region (i.e. second stage deformation) on the state of retained austenite in a typical composition of duel phase steel with reduced amount of silicon.

2. Materials and methods

The composition of steel under investigation is given in Table 1. A cast ingot of steel was hot-rolled to a final thickness of 14 mm following a classical rolling procedure at CANMET, Ottawa. All hot deformation programs were carried out on a computerized Material Testing System (MTS), adopted for compression test. Basically, the equipment is composed of a MTS automated testing machine coupled with a radiant furnace and a tool geometry that allows for quenching of specimens at any time. The compression specimens were machined from the as-received plates with their longitudinal axis parallel to the rolling direction.

To design any TMP schedule, the three critical temperatures of steel are required to be identified. These are non-recrystallization temperature (T_{nr}), austenite-to-ferrite (Ar_3), and austenite-to-pearlite transformation start temperatures. These temperatures were measured by Continuous Cooling Compression (CCC) testing [13]. Fig. 1 shows the CCC true stress–temperature curve, together with microstructural verification of detected point for Ar_3 for the steel used in this study.

The TMP scheme, which is of a typical discontinuous cooling path (i.e. multiple cooling stages), is schematically represented by Fig. 2. Table 2 summarizes the two sets of deformation conditions at non-recrystallization region, which have been used in the present study.

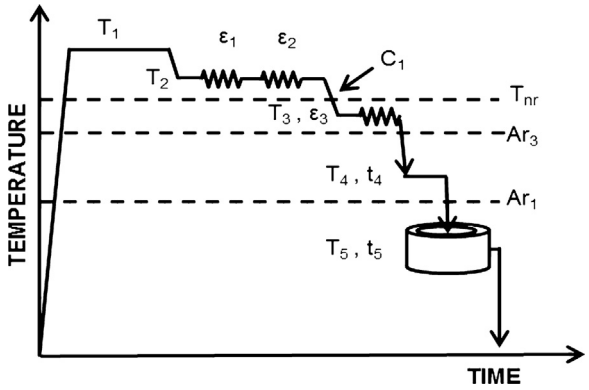

Fig. 2. Schematic diagram of heat and deformation schedule applied in the present study.

Those parameters, which were kept constant throughout the deformation or cooling program, have been optimized elsewhere [2,10–14].

Microstructural studies were carried out using optical and scanning electron microscopy. To avoid mechanical transformation of retained austenite during sample preparation, specimens were electrolytically polished and then prepared using a particular tint etching method, adopted from Le Pera's technique [15]. After tint etching, the M/A phase appeared white which could be easily distinguished in black and white mode pictures. A developed tint-etching method was also employed to reveal the retained austenite characteristics (for instance, dispersion and overall morphology) and existence of any pearlite pockets within microstructure [16]. Following this method, retained austenite appeared white, polygonal ferrite and bainite orange to brown color, pearlite as dispersed black particles, and martensite as blue. For detailed observation at higher magnification, specimens were examined by scanning electron microscopy.

The RA measurement was carried out by Mössbauer spectroscopy, using backscatter method at a working voltage of 7 kV. It has been reported that Mössbauer technique is more sensitive and more accurate than X-ray diffraction, when the retained austenite content is small [17]. Fig. 3 shows Mössbauer spectrum of the sample deformed at 850 °C to true strain of −0.25.

The carbon content of retained austenite was measured by X-ray diffraction using the lattice parameter extrapolation method and the following empirical equation [18]:

$$a_0 = 3.578 + 0.044\%C \quad (1)$$

3. Results and discussion

3.1. Effect of strain in non-recrystallization region

In order to investigate the effect of strain in austenite non-recrystallization region on the ferrite grain refinement and on the characteristics of other transformation products of austenite, samples were subjected to two identical hits at 1050 °C followed by cooling to 850 °C at a constant rate of 3 °C/s. Samples were, then, deformed isothermally at this temperature to various true strains of 0, −0.15, −0.25, and −0.35. Subsequent to third deformation, all specimens were intercritically-annealed followed by a short bainitic holding at 450 °C and then water quenched to room temperature (Fig. 2).

Fig. 4 shows variation of retained austenite volume fraction (V_{RA}) and its carbon content (C_{RA}%) as well as the volume fraction of other microconstituents as a function of strain in non-recrystallization region. Fig. 5 shows the optical and corresponding scanning electron micrographs of samples deformed to various