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Microstructural evolution and mechanical properties of dual phase steel produced by strip casting

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ABSTRACT

In the present study, an as-cast strip of dual phase steel (Fe-0.16C-0.3Si-0.81Mn-0.03Ti wt%) was successfully produced by twin-roll strip casting (TRSC) process. The as-cast strip was subjected to two different processing routes. The microstructure of the as-cast strip, cold-rolled sheet and annealed sheet was studied and related to mechanical properties of the annealed sheet. It was observed that the as-cast strip microstructure consisted of grain boundary ferrite, Widmanstatten ferrite, pearlite and intragranular ferrite, and the solidification structure was characterized by dendritic structure without the equiaxed center zone. The microstructure consisted of ferrite, martensite and non-recrystallization (N-R) region was obtained in the annealed sheet when the as-cast strip was directly cold rolled and annealed at 740–780 °C for 3 min. However, a typical dual phase microstructure of ferrite-martensite was obtained in the annealed sheet when the martensitic structure in the as-cast strip was subjected to cold rolling and annealing at 740–780 °C for 3 min. The dual phase microstructure in the annealed sheet having martensite fraction of ~ 51–77% was obtained, leading to tensile strength of ~ 851–914 MPa and corresponding total elongation of ~ 16–11%. Tempering treatment reduced martensite hardness, leading to lower tensile strength (~ 702–518 MPa) and corresponding higher total elongation (~ 19.8–30%) compared to non-tempered steel.

1. Introduction

Safety, energy saving and environmental protection are the major needs in the modern automobile industry, where there is a focus on advanced high strength steels (AHSS) [1]. Dual phase (DP) steels are typical advanced high strength steels (AHSS) and are widely used in the automotive industry [2,3]. The characteristics of DP steels include continuous yielding behavior, high elongation, low yield stress-to-tensile strength ratio and high work hardening rate [3–7]. Dual phase microstructure can be obtained in cold-rolled DP steels by intercritical annealing treatment (IAT) in the two phase temperature region of austenite-ferrite, followed by rapid cooling to room temperature to transform austenite to martensite. The mechanical properties of DP steels are mainly influenced by ferrite-to-martensite ratio, grain size and morphology of ferrite and martensite. Previous studies suggested that the yield strength and tensile strength of DP steels increased with increase of martensite fraction, while total elongation was decreased [8,9]. Refinement of ferrite and/or martensite grain can enhance the strength and ductility of DP steels [10]. Martensite when present as isolated grain within the ferrite matrix provides superior mechanical properties compared to its presence as a chain-like network structure along the ferrite grain boundary [11]. Moreover, microstructure and mechanical properties of DP steels influenced by tempering treatment has also been studied [12,13]. Tempering treatment can change martensite morphology and other structural characteristics.

In the industry, cold-rolled DP steels are produced by a long and complex production line, consisting of continuous casting, reheating, rough rolling, finish rolling and cold rolling followed by annealing. The conventional production line requires significant cost and energy and is not good from the viewpoint of environmental protection. As an alternative, twin-roll strip casting (TRSC) process is a more economical and environment friendly approach to produce cold-rolled DP steels [14,15]. TRSC process can directly produce thin strip steel (1–5 mm) from the molten steel. Compared to the conventional steel line, the strip steel can be produced without reheating, rough rolling and finish rolling by TRSC process, which can shorten the strip steel line to ~

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Table 1
Chemical composition of the experimental steel (wt%).

C	Si	Mn	Ti	Fe
0.16	0.3	0.81	0.03	Bal.

60 m [16]. Silicon steels, low-carbon steels, high-manganese steels, TRIP steels and stainless steels produced by strip casting have been studied [17–21]. Conventional DP steels produced by strip casting have been studied by way of simulation in the laboratory [22,23]. However, there are no studies on the microstructure and mechanical properties of cold-rolled DP steels produced by strip casting.

In the present study, a Fe-0.16C-0.3Si-0.81Mn-0.03Ti wt% DP steel was produced via TRSC process in the laboratory. Two processing routes were adopted to process the as-cast strip. The microstructure in each processing route was characterized using optical microscope, scanning electron microscope and transmission electron microscope. The tensile properties and hardness of the annealed sheets were also studied. The objective of the study described here is to explore the microstructure and mechanical properties of DP steel produced by strip casting.

2. Experimental material and procedure

The chemical composition of the experimental steel is listed in Table 1. Fig. 1 shows fraction of equilibrium phases in the temperature range of 650–900 °C calculated using Thermo-Calc software combined with TCFE6 database. In Fig. 1, the start temperature and finish temperature of transformation from ferrite and Fe_3C to austenite were 703 °C and 711 °C, respectively.

The as-cast strip was produced by a twin-roll strip caster (vertical type) available at the State Key Laboratory of Rolling and Automation (RAL). The roller width and diameter of cast rollers were 110 mm and 500 mm, respectively. Fig. 2 shows the schematic diagram of processing route for the experimental steel. A vacuum induction furnace (capacity 50 kg) was used to melt liquid steel. The liquid steel was poured into a pre-heated tundish (1180 °C) and subsequently allowed to flow into cast rollers forming a molten pool. Next, the liquid steel was solidified and deformed by cast rollers (roller gap 2.2 mm, casting speed 30 m/min). Lastly, the as-cast strip was firstly cooled to 950 °C by water and then was cooled to room temperature in air. The thickness of the as-cast strip was ~ 2.2 mm. Subsequently, two different processing routes were adopted to process the as-cast strip: (I) the as-cast strip was directly cold rolled to 0.8 mm with 64% reduction and then annealed at 720–780 °C for 3 min (heating rate of ~ 15 °C/s), followed by water quenching. The cold-rolled sheet is referred here as DCR and the cold-rolled sheet

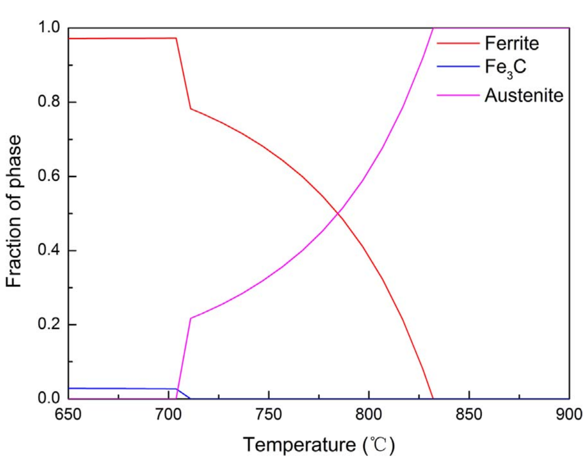

Fig. 1. Fraction of equilibrium phases in the temperature range of 650–900 °C calculated using Thermo-Calc software combined with TCFE6 database.

annealed at 720, 740, 760 and 780 °C are referred as DA72, DA74, DA76 and DA78, respectively. (II) To obtain a martensitic structure, the as-cast strip was heat treated at 1050 °C for 10 min, followed by quenching. The subsequent cold rolling and annealing processes were identical to route (I). In this condition, the cold-rolled sheet referred as HCR and the cold-rolled sheet annealed at 720, 740, 760 and 780 °C are referred as HA72, HA74, HA76 and HA78, respectively. Moreover, HA74 steel was tempered at 200, 400 and 600 °C for 20 min. The HA74 steel samples tempered at 200, 400 and 600 °C are referred as T200, T400 and T600, respectively.

Metallographic specimens were cut from the as-cast strip, cold-rolled sheet and annealed sheet, and they were mechanically polished using standard metallography procedure. The solidification structure of the as-cast strip was etched with Dickenson solution and the as-cast microstructure, cold-rolled sheet and annealed sheet microstructure were etched with 4% nital (time 15 s) for microstructural characterization using OLYMPUS-BX53M optical microscope (OM) and FEI QUANTA 600 scanning electron microscope (SEM). To observe the fine structure of as-cast strip and annealed sheet, transmission electron microscopy (TEM) studies were carried out using a FEI Tecnai G^2 F20 microscope (voltage 200 kV). TEM specimens (diameter 3 mm) were first ground to a thickness of 50 μm and then twin-jet electro-polished at − 25 °C in a solution containing alcohol and perchloric acid in the proportion of 7:1. The fraction of martensite in the annealed sheet was quantified using the image processing software, Image Pro Plus.

Tensile specimens of dimensions 10 mm (gauge length) × 3.2 mm (width) × 0.8 mm (thickness) were machined with longitudinal axis parallel to the rolling direction. The tensile test was performed using a universal testing machine (room temperature, crosshead speed 1 mm/min). Macro-hardness measurement was carried out by FM-700 Vickers hardness testing machine (load 500 g). A TI-900 Hysitron triboindenter (load 2000 μN) was used to test the hardness of martensite and ferrite. A reference specimen of fused silica was used to calibrate the Berkovich nanoindenter. Specimen for nanoindention was mechanically polished and etched with 4% nital (time 4 s).

3. Results

3.1. Solidification structure and as-cast microstructure

Fig. 3 shows OM micrograph of solidification structure of the as-cast strip. It was observed that the solidification microstructure was characterized by directionally solidified dendrites that nucleated at the cooled cast roller surface and grew towards the roller gap. There was no obvious equiaxed structure in the center of the as-cast strip, which was similar to the solidification structure of as-cast strip of low-carbon steel reported previously [24]. With increase in the distance from the as-cast strip surface toward the center, the secondary arms were clearly observed and the dendritic structure was coarse. The inclination of primary dendrite arm was ~ 10–35° from the thickness direction of the as-cast strip. This was caused by the relative flow of liquid steel [25].

Fig. 4 shows OM and TEM micrographs of as-cast microstructure of as-cast strip. It can be seen that prior austenite grain was revealed by grain boundary ferrite, marked by arrow in Fig. 4(a). The shape of prior austenite grains was columnar and equiaxed along the two sides and center, respectively. The columnar prior austenite grain size was ~ 200–700 μm, and the equiaxed prior austenite grain size was ~ 100-180 μm. The as-cast microstructure of the as-cast strip mainly consisted of grain boundary ferrite, Widmanstatten ferrite, pearlite and intragranular ferrite, as shown in Fig. 4(b), which was consistent with the study of similar grade of strip cast steels [18]. The Widmanstatten ferrite in the as-cast strip was also revealed by TEM, as shown in Fig. 4(c). Usually, Widmanstatten ferrite is easy to form at the coarse prior austenite grain boundary [26], which is a typical characteristic of strip cast low-carbon steel microstructure [18,27]. Moreover, rod-like cementite was present in the as-cast strip, as shown in Fig. 4(d), and