Effect of cooling process on mechanical properties of thin-gauge hot-rolled dual-phase steel

B Liu¹², R Wu¹*, J Hu²

¹Key Laboratory for Ferrous Metallurgy and Resources Utilization of Ministry of Education, Wuhan University of Science and Technology, Wuhan 430081, China
²Wuhan Branch of Baosteel Central Research Institute, Wuhan 430080, China

*E-mail: runwu@wust.edu.cn

Abstract. The high strength hot-rolled dual-phase steel suitable for a thin slab continuous casting and rolling (TSCR) process was developed by a low C and Nb micro-alloyed design with the controlled rolling and cooling technology. The effect of the isothermal temperature and holding time on the microstructure and mechanical properties of the dual-phase steel was studied using a uniaxial tensile test and optical microscope (OM). The results showed that with the decrease of the isothermal temperature in the ferrite phase transformation region, the thermodynamic conditions of the ferrite transformation were enhanced. The proportion of the ferrite increased while that of martensite decreased, resulting in the reduction of the yield strength and tensile strength and the increase of elongation. With the rise in the isothermal time, the kinetic conditions of the ferrite transformation were enhanced and the proportion of the ferrite increased. The ferrite transformation has completed after 8 seconds of the isothermal holding time, and it was not apparent for increased amount of the transformed ferrite to increase the isothermal time.

1. Introduction

With a rapid development of the lightweight work for automobile, the advanced high-strength steel (AHSS) has been widely used in body-in-white and structural parts in vehicles [1-4]. Dual-phase steel is one of the most commonly used advanced high strength steels in the automotive industry due to its excellent combination of strength and plasticity, low yield ratio, and high initial work-hardening rate [5-9]. In recent years, with the development of hot rolling equipment capacity and manufacturing technology, there is a significant improvement in a plate shape, size, surface quality and mechanical properties for the hot-rolled steel strip. Especially the thin gauge hot-rolled plate produced by thin slab continuous casting and rolling process has been able to meet the requirements of the manufacture of body-in-white and related structural parts. Through the "hot rolled steel on behalf of the cold rolled steel", the cold rolling and annealing processes in the strip steel production process can be reduced, which dramatically reduces the energy consumption of iron and steel materials manufacturing [10-12]. Therefore, the development of thin gauge hot-rolled dual-phase steels has become a new hot spot for the advanced high strength steels.

At present, the hot-rolled dual-phase steel was studied mainly for the traditional hot rolling process, and the carbon content was generally between 0.08% and 0.16% [13,14]. Due to the limitations of the peritectic region, there were only a few studies on the thin gauge dual-phase steel for the TSCR process, especially the tensile strength above 750 MPa. In this paper, the low-carbon and Nb micro-
alloyed high-strength dual-phase steels were designed for the laboratory experiment with a controlled cooling process using salt bath cooling process, which provided a theoretical basis for the production of 750 MPa dual-phase steel in the TSCR process.

2. Experimental
The experimental steel was vacuum-melted and cast into a 50 kg ingot. The composition is shown in table 1.

| Table 1. The chemical composition of tested steel (wt, %) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| C               | Si              | Mn              | P               | S               | Al              | Nb              | Cr              |
| 0.07            | 0.28            | 1.58            | 0.016           | 0.005           | 0.035           | 0.037           | 0.51            |

The experimental method was as follows. The ingot was heated to 1200 °C for 1 hour and then cast into a slab with a thickness of 30 mm. The slab was then hot-rolled to a thickness of 3.0 mm (30mm→18mm→12mm→8mm→5mm→3mm). To investigate the influence of the isothermal temperature and time of the ferrite transformation region on the microstructure and mechanical properties of the steel, the sample after hot-rolling was put into the salt bath furnace for ultra-rapid cooling, and the cooling process was controlled with different isothermal temperatures and isothermal time periods. After the salt bath, the sample was subjected to water quenching to obtain the martensite structure. The experimental process is shown in table 2.

| Table 2. Processing parameters of controlled cooling of tested steel |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| No.             | Final rolling temperature/°C | Isothermal temperature/°C | Isothermal time/s | Water quenching temperature/°C |
| 1               | 810             | 700             | 8               | <200            |
| 2               | 670             | 640             | 8               |                 |
| 3               | 640             | 640             | 8               |                 |
| 4               | 640             | 640             | 2               |                 |
| 5               | 640             | 640             | 15              |                 |

The mechanical properties were measured according to GB/T 228.1-2010, and the specimens were machined along the rolling direction with a gauge length of 50 mm after water quenching. After grinding, polishing and etching in 4% nitral, the microstructure was observed by a Neophot-type optical microscope (OM). The relative amounts of each phase were analyzed quantitatively. The slices were first ground down to 80 μm thickness and then twin-jet polished by Tenupol-5 double-spray electrolyzer. Finally, the fine microstructure was observed by JEM-2100F transmission electron microscopy (TEM).

3. Experimental results
3.1 Microstructure
The microstructure features of the experimental steel at different isothermal temperatures and isothermal times are shown in table 3 and figure 1. The microstructure was ferrite and martensite dual-phase structure for all the experimental steels. With the decrease of isothermal temperature, the proportion of ferrite gradually increased, and the percentage of martensite gradually decreased. The proportion of martensite was 89.2% for sample 1#, 60.6% for sample 2# and 51.8% for sample 3#. With the increase of isothermal time, the proportion of ferrite increases gradually, and the percentage
of martensite decreased gradually. The percentage of martensite was 87.1% for sample 4# and 50.3% for sample 5#.

Table 3. The quantitative metallographic results of the tested steels

| No. | Microstructure | F/%  | M/%  |
|-----|----------------|------|------|
| 1   | F+M            | 10.8 | 89.2 |
| 2   | F+M            | 39.4 | 60.6 |
| 3   | F+M            | 48.2 | 51.8 |
| 4   | F+M            | 12.9 | 87.1 |
| 5   | F+M            | 49.7 | 50.3 |

Figure 1. OM images of the steels microstructures (Black areas refer to martensite and gray/white ones to ferrite): (a) Sample 1#; (b) Sample 2#; (c) Sample 3#; (d) Sample 4#; (e) Sample 5#

3.2 Mechanical properties
The mechanical properties of the experimental steels are listed in table 4. The tensile strength (TS) was over 750 MPa for all the samples, the yield strength (YS) was between 425 and 683 MPa, the elongation was between 10.5% and 18.0% and the yield ratio were below 0.70.

Table 4. Mechanical properties of the steels

| No. | YS/MPa | TS/ MPa | A50mm/% | YS/ TS |
|-----|--------|---------|---------|--------|
| 1   | 693    | 1001    | 10.5    | 0.69   |
| 2   | 593    | 927     | 14.0    | 0.64   |
| 3   | 504    | 846     | 17.5    | 0.60   |
| 4   | 572    | 903     | 14.0    | 0.63   |
| 5   | 425    | 768     | 18.0    | 0.55   |

3.3 Discussion
The relationships between the isothermal temperature/time and the mechanical properties of experimental steels were shown in figure 2. The influence of the isothermal temperature on the microstructure and features of the experimental steel was mainly due to the decrease in the ferrite phase transformation temperature. The degree of the undercooling for ferrite transformation increased, and the thermodynamic conditions were enhanced. So, with the same holding time, the amount of the transformed ferrite increased. At the same time, the degree of undercooling (ΔT) for the retained austenite to martensite phase transformation decreased. According to the martensite phase transformation kinetic equation (1), the martensite volume fraction depended on the degree of undercooling (ΔT) but was irrelevant with the time [15], so that the proportion of martensite after water quenching decreased. For the mechanical properties, as the isothermal temperature dropped, the amount of the ferrite increased so that the yield strength and tensile strength decreased and the elongation increased.

\[ f = 1 - 6.956 \times 10^{-5} \times (455 - \Delta T)^{5.32} \]  

(1)

At the same isothermal temperature (640 °C), the kinetic conditions of the ferrite transformation were enhanced with the increase of the isothermal time. Besides, since the isothermal temperature was set at 640 °C, the ferrite transformation degree of undercooling was high, and there were enough thermodynamic conditions to promote the ferrite transformation. Therefore, there was 12.9% transformed ferrite with a short isothermal time of 2 seconds. The short time ferrite transformation avoided the ferrite coarsening during the isothermal process, which made the elongation of the experimental steel reach 14.0%. The amount of ferrite was nearly the same for the isothermal time of 8 seconds and 15 seconds. Most ferrite transformation has been completed after 8 seconds of isothermal holding, and it was not apparent for the increased amount of the transformed ferrite to increase isothermal time. After 15 seconds isothermal holding, the amount of ferrite transformation increased a little, but the ferrite grain size increased (as showed in figure 1e), which resulted in the significant decrease of the yield strength.

(a) temperature  

(b) time  

Figure 2. The relationships between the isothermal temperature/time and the mechanical properties.
temperature. Meanwhile, the martensite proportion was lower in sample 3#, and the size of the martensite was relatively small, as compared to samples 1# and 2#.

The effect of the isothermal time on the TEM microstructure was also investigated. It can be seen that the proportion of the ferrite increased and the percentage of the martensite decreased with the increase of the isothermal time under the condition of the isothermal temperature of 640°C (as shown in figure 3c-figure 3e). When the isothermal time was 2 seconds, due to the short ferrite phase transformation time, the amount of transformed ferrite was less, and the martensite proportion was as high as 87.1% in sample 4#, which was close to the martensite proportion in sample 1# experimental steel. However, the isothermal temperature was lower for sample 4# than sample 1# so that the grain size was finer in sample 4#. When the isothermal time was increased to 15 seconds, there was more ferrite formed by the ferrite phase transformation. The martensite proportion in sample 5# was the lowest, and the grain size was relatively coarse. Therefore, the yield strength and tensile strength of sample 5# were the lowest in all the test steels.

4. Conclusions
✓ The ferrite and martensite dual-phase structure of hot-rolled C-Mn-Nb-Cr steel with a tensile strength over 750 MPa was obtained through a controlled rolling and a cooling process with the salt bath isothermal holding-water cooling process
✓ With the decrease of the isothermal temperature in the ferrite transformation region, the thermodynamic conditions of the ferrite transformation were enhanced, the proportion of the ferrite increased, the proportion of the martensite decreased, the yield strength and the tensile strength decreased, and the elongation increased.
✓ With the increase of the isothermal time in the ferrite transformation region, the kinetic conditions of the ferrite transformation were enhanced, and the proportion of the ferrite increased. Most
ferrite transformation has been completed after 8 seconds of isothermal holding time, and it was not apparent for the ferrite transformation to increase the isothermal time.

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