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Development of Ultra-High Strength Linepipes with Dual-Phase Microstructure for High Strain Application†

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Abstract:

Extensive studies have been conducted to develop high strength linepipes with higher deformability. One of the key technologies for improving deformability is dual-phase microstructural control. Steel plate with ferrite-bainite microstructure can be obtained by applying thermo-mechanical controlled processing (TMCP), a process of controlled rolling and accelerated cooling. Low carbon, boron-free steels were used to enable the ferrite formation during cooling after controlled rolling, and accelerated cooling with an ultimate cooling rate enhanced the strength up to the X120 grade. HOP® (Heat-treatment On-line Process) was also applied after accelerated cooling in order to improve the Charpy energy of the base material. Trial production of X120 high deformability linepipe was conducted by applying dual-phase microstructural control. Microstructural and mechanical properties of X120 linepipe are introduced in this paper.

1. Introduction

There has recently been a growing demand for higher grade linepipes that can help reduce the total cost of long-distance pipelines. The application of high-strength linepipes such as API X70 and X80 grades has therefore been increasing in recent years, and the X100 grade was put to practical use for the first time in 2002[1]. Developments have been also conducted on X120 linepipes. On the other hand, pipeline developments have been expanded toward environmentally severe regions such as permafrost and seismic regions. The linepipes installed in these regions, where ground movements can be expected to impose larger strains, must have deformability sufficient to prevent local buckling and girth weld fracture.

Thermo-mechanical controlled processing (TMCP), a process of controlled rolling and accelerated cooling, is applied for producing high strength linepipe steels. Fine bainitic microstructures obtained by accelerated cooling confer a good balance of high strength and toughness. In order to increase the strength to X120 grade, a lower bainite microstructure obtained by the addition of boron is applied[2,3]. It becomes difficult, however, to balance high strength and high deformability in steel with a single bainitic microstructure. Deformability of linepipe is strongly affected by microstructure of the steel. Steels with a dual-phase microstructure are well known to exhibit higher strain hardenability and superior deformability[4]. By applying ferrite-bainite microstructural control, high-deformability linepipes of up to grade X100 have been developed[5].

In this paper, design concept for improving deformability while balancing high strength and toughness of the base material of ultra-high strength linepipes are introduced from the metallurgical point of view. Trial production results of high deformability X120 linepipes are also presented.

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2. Dual-Phase Microstructural Control for X100 and X120 Linepipe

2.1 Effects of Plate Rolling Conditions on Microstructure

The production of a ferrite-bainite dual-phase microstructure by TMCP requires precise temperature control during the plate rolling. Therefore, the effect of accelerated cooling conditions on the microstructure was investigated by conducting a laboratory plate-rolling test on steel with a chemistry of 0.08C-0.25Si-1.5Mn-0.04Nb. After the steel plates were hot rolled, accelerated cooling was applied at different temperatures. **Figure 1** shows the effect of the accelerated cooling starting temperature on the bainite volume fraction. The accelerated cooling starting temperature is expressed as the temperature subtracted by the Ar_3 temperature, the ferrite transformation starting temperature, under continuous cooling.

Bainite volume fraction was 100% when the accelerated cooling starting temperature was above the Ar_3 temperature, and it decreased as the accelerated cooling starting temperature fell below the Ar_3 temperature. **Figure 2** shows the relation between uniform elongation and the bainite volume fraction. The highest uniform elongation was obtained by steel with a bainite volume fraction of around 50%.

According to the experimental and analytical studies on the effect of the microstructure on deformation behavior of ferrite-bainite steel, *Y*/*T* ratio or *n*-value was strongly influenced by the bainite volume fraction, as well as the strength difference between the soft phase and hard phase. Therefore, it can be assumed that the optimum bainite volume fraction depends on the chemistry and plate manufacturing conditions. It can also be concluded that it is very important to optimize the microstructure by precise control during the plate manufacturing process, in order to produce high-deformability linepipes.

2.2 Effect of Boron on Transformation Behavior

Boron is a useful element to increase strength with a relatively lower chemistry. However, dual-phase microstructural control becomes very difficult in boron-added steels. **Figure 3** shows continuous cooling transformation (CCT) diagrams for boron-free and boron-added steels. Ferrite forms in the boron-free steel during slow cooling at around 700°C, whereas ferrite formation is almost wholly absent in the boron-added steel. Another difference between the CCT diagrams is a lower bainite transformation temperature for the boron-added steel. This addition of boron apparently promotes the transfor-

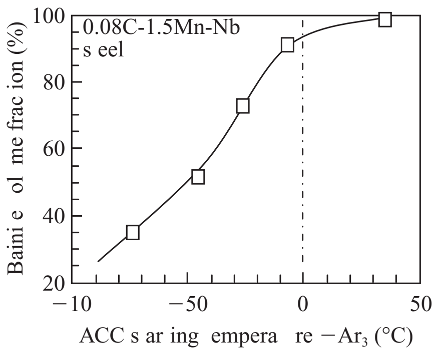

Fig. 1 Effect of accelerated cooling starting temperature on bainite

mation of lower bainite, and this confers a large bene t lower Y/T ratio even in higher strength regions. Therefore, dual-phase microstructural control is essential measure for balancing high strength and deformability, especially for X120 grade linepipe steel.

2.4 Effect of On-Line Heat Treatment on the Charpy Energy of the Ferrite-Bainite Steel

Charpy absorbed energy is required for the prevention of running ductile fractures. A lower rolling finish-

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test results demonstrate that a design temperature of