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Material Design of Hot-rolled Steel Coils for Heavy Wall X70 Spiral Linepipes

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Higher strength and toughness has been required for linepipe steels using for long-distance pipelines of natural gas transportation. To achieve high strength and drop weight tearing test properties for heavy wall X70 spiral linepipes, the microstructure refinement of bainitic ferrite is essential in hot-rolled steel coils. Niobium addition is very effective to have precipitation strengthening and bainitic ferrite grain refinement through the increase of controlled rolling ratio in austenite non-recrystallization region. Laboratory rolling test results indicated that low-carbon, high-niobium steel had excellent strength–toughness balance by increasing the amount of finer NbC precipitates by 20 nm or less in a fine bainitic ferrite microstructure. From laboratory welding joint test results, low-carbon, high-niobium steel showed good heat-affected zone toughness with a relatively finer prior austenite grain size in spite of a higher martensite–austenite volume fraction.

LIST OF ABBREVIATIONS

CR	Controlled rolling
T_{nr}	Non-recrystallization temperature
T_R	Complete non-recrystallization temperature ($T_{nr} - 75°C$)
CG-HAZ	Coarse grain heat affected zone
DWTT	Drop weight tearing test
vTrs	50% ductile-brittleness transition temperature in Charpy impact test
Ceq	Carbon equivalent value
*Ar*3	Temperature at which ferrite begins to form
Nb_{sol}	NbC soluble temperature
ICP	Inductively coupled plasma
EBSD	Electron back-scattered diffraction
IPF	Inverse pole figure
t_{50}	Time of 50% austenite recrystallization (sec)
T	Temperature (K)
X_v	Austenite recrystallization ratio: time of 50% austenite recrystallization (sec)

INTRODUCTION

Higher strength and toughness has been required for linepipe steels to achieve safety and reliability in long-distance pipelines of natural gas transportation. It is well known that austenite grain refinement during hot rolling is an effective way to improve low-temperature toughness of steels evaluated with drop weight tearing tests (DWTTs) and Charpy impact tests (Matsuda et al., 1971). A larger austenite grain gives a larger bainitic ferrite grain size after bainite transformation, and it deteriorates the toughness of plate steels and hot-rolled steel coils (Kozasu et al., 1977). It is very important to apply controlled rolling (CR) in the austenite non-recrystallization region and control properly the rolling reduction ratio in each rolling temperature region, such as the austenite recrystallization, partially austenite recrystallization, and austenite non-recrystallization regions (Irvine et al., 1970; Tanaka et al., 1982).

High-niobium (Nb) steels have been developed for plate steels and linepipe steels with lower alloy cost design (Siciliano et al., 2008; Bai et al., 2011; Gray, 2014). It is well known that high-Nb steels show a higher T_{nr} (non-recrystallization temperature) compared with conventional low Nb steels (Hansen et al., 1980; Cuddy, 1982; Bai et al., 1993; Calvo et al., 2009). Therefore, high Nb steels can obtain a higher CR ratio in austenite non-recrystallization region below T_R temperature (complete non-recrystallization temperature, $T_{nr} - 75°C$) more easily than low-Nb steels. There are mainly two types of mechanisms for this phenomenon, pinning effects of austenite grain growth by NbC precipitates and solute drag effects by solute Nb atoms. Then, pinning by NbC precipitates is considered to be the dominant mechanism (Hansen et al., 1980). However, the mechanism of austenite recrystallization suppression effect is not clear enough in high-Nb steels regarding the size of NbC precipitation, its distribution, and the balance of Nb and C content.

In this study, to clarify the effects of the amount of NbC precipitates at every size on austenite recrystallization behavior and mechanical properties after bainite transformation, laboratory rolling tests were conducted using several samples with different Nb and C content levels. The amount of NbC precipitates and solute Nb were analyzed separately for each NbC size: NbC size of 20 nm or less, NbC size between 20 nm and 100 nm, and NbC above 100 nm. Then, the effects of NbC size distribution and its amount on austenite recrystallization behavior and the strength–toughness balance were studied. The increase of Nb and C content may deteriorate the heat-affected zone (HAZ) toughness. In this study, the effect of Nb content on the toughness of the simulated coarse grain heat-affected zone (CG-HAZ) and actual welded joint was also investigated.

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KEY WORDS: Austenite, recrystallization, controlled rolling, niobium carbide, precipitation, bainite, toughness.