Recent Development in Microstructural Control Technologies through the Thermo-Mechanical Control Process (TMCP) with JFE Steel's High-Performance Plates†

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Abstract:

Thermo-mechanical control process (TMCP) is a microstructural control technique combining controlled rolling and cooling. Thermo-mechanical control process is used to obtain excellent properties for steel plates, such as high strength, excellent toughness, and excellent weldability. JFE Steel has been developing TMCP technologies ever since it started operating its accelerated cooling facility, OLAC® (On-Line Accelerated Cooling), in its plate mill at West Japan Works (Fukuyama) in 1980 (the world's first industrial accelerated cooling system ever built). In 1998, JFE Steel developed Super-OLAC, an advanced accelerated cooling system capable of cooling plates homogeneously at high cooling rates close to the theoretical limits. In 2004, the epoch-making on-line induction heating facility, HOP® (Heat-treatment On-line Process), was also installed in the plate mill at West Japan Works (Fukuyama). High-strength steels, a grade of steel usually produced by the quenching and tempering (Q-T) process, can be toughened by refining the component carbides through rapid tempering by HOP. Because Super-OLAC is capable of accurately controlling the stop cooling temperature before tempering, JFE has managed to develop a new set of microstructural control techniques using M-A (martensite-austenite constituent) as the hard phase. These are unique techniques unachievable with the conventional Q-T process or conventional TMCP. These techniques have already been applied to various advanced products. In this paper, the fundamentals of microstructural control by TMCP, and the recent development of TMCP are described. Examples of the advanced high-strength plates produced in JFE Steel are also presented.

1. Introduction

Thermo-mechanical control process (TMCP) is a microstructural control technique combining controlled rolling and cooling. TMCP is used to obtain excellent properties for steel plates, such as high strength, excellent toughness, and excellent weldability. In 1980, JFE Steel started operating OLAC® (On-Line Accelerated Cooling), the world's first industrial accelerated cooling facility, in the plate mill at JFE Steel's West Japan Works (Fukuyama)[1,2]. In 1998, JFE Steel developed *Super*-OLAC[5], an advanced accelerated cooling system capable of cooling plates homogeneously at high cooling rates close to the theoretical limits.

TMCP strengthens and toughens steel plates essentially by refining the transformed microstructures. TMCP can also reduce alloying addition, and thus realizes other merits such as improved weldability. JFE Steel has also established JFE EWEL®, a microstructural control technology for the heat-affected zone (HAZ) in high-heat-input welding, to ensure the excellent mechanical properties of welds performed by customers[3,4]. Needless to say, the TMCP technology with *Super*-OLAC is essential to JFE EWEL®.

high-strength steel plates with yield strengths of 960 and
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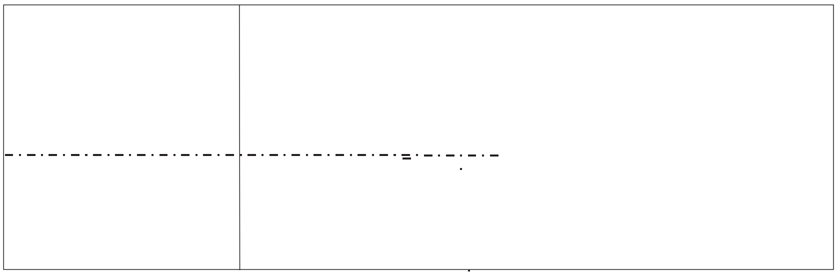

a fine and equiaxed M-A morphology through process control, and also to refine the microstructure of the matrix. An optimal combination of alloy design, ausforming, and processing, especially heat cycles after hot rolling, is essential to obtain high strength with low yield ratio and excellent toughness, using M-A.

Figure 6 shows the concept of the microstructural control technology using M-A to obtain high-strength steel plates with low yield ratios through the *Super*-OLAC + HOP process.

The hot rolling is finished in the non-recrystallized temperature range to accumulate plastic strain in austenite. Then, accelerated cooling is applied to the plate by *Super*-OLAC. The accelerated cooling is interrupted between the bainite transformation start temperature (B_s) and the bainite transformation finish temperature (B_f). At this stage, the microstructure consists of bainite and the remaining austenite.

Then, the plate is rapidly heated by HOP to temperatures below the Ac_1 temperature. Supersaturated carbon in bainite diffuses into the remained austenite, and the bainite recovers during the treatment. The remaining austenite with high hardenability due to the high carbon content subsequently transforms to M-A as the plate cools to ambient temperature. The *Super*-OLAC + HOP process can produce high-strength steel plates with tensile strengths of over 600 MPa and low yield ratios, with a microstructure consisting of a hard phase (M-A) and a soft phase (tempered bainite).

Photo 2 shows a typical microstructure of the steel plate produced by the *Super*-OLAC + HOP process, taken by a scanning electron microscope (SEM)[15]. The bright phase is M-A (hard phase) and the dark phase is tempered bainite (soft phase). The volume fraction of M-A was about 13%. The mechanical properties of a 25 mm-thick plate are shown in **Table 1**. The plate showed a high tensile strength of over 900 MPa, a low yield ratio of under 80%, and high absorbed energy of 216 J in Charpy impact tests at 0°C. The weldability and mechanical properties of the welded joint were also excellent in this plate[15].

The microstructural control technology by the *Super*-OLAC + HOP process using M-A as a hard phase has already been applied to high-strength steel plates with tensile strengths of over 600 MPa and excellent deformability (e.g., the 780 MPa grade plates with low yield ratios for building constructions,[15] and the plates for X80 grade linepipes with excellent deformability (JFE-HIPER))[17]. The plates produced by this process are also reported to suppress marked hardening with strain aging, because of the reduced carbon content and dislocation density in the matrix[17].

4. Concluding Remark

This paper has reviewed recent developments in microstructural control technologies through the thermo-mechanical control process (TMCP) applied for JFE Steel's advanced steel plates. Though metallurgical phenomena such as recovery, recrystallization, precipitation, and transformation are individually simple, as described in the textbooks, the infinite combinations of these phe-