JFE TECHNICAL REPORT
No. 11 (June 2008)

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 prop-

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[†] Originally published in *JFE GIHO* No. 18 (Nov. 2007), p. 1–6

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erties of welds performed by customers[3,4]. Needless to say, the TMCP technology with *Super*-OLAC is essential to JFE EWEL®.

In 2004, JFE Steel started operation of an epoch-making on-line induction heating facility, HOP®(Heat-treatment On-line Process), in the plate mill at West Japan Works (Fukuyama)[6]. High-strength steel with a tensile strength of over 600 MPa, a type usually manufactured by quenching and tempering (Q-T), can be produced by the *Super*-OLAC + HOP process online without any off-line heat treatment. Production capacities have been greatly increased and the lead-time from order to delivery has been shortened. And as an added advantage, the rapid tempering by HOP improves the toughness of the high-strength steels by refining carbides[7–9].

Because *Super*-OLAC + HOP is capable of accurately controlling the stop cooling temperature before tempering, JFE Steel has been able 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 conventional Q-T or conventional TMCP. These new microstructural control technologies have already been applied for various high-strength steel plates.

This paper describes recent developments in TMCP, including the *Super*-OLAC + HOP process, with some examples of advanced steel plates produced in JFE Steel.

2. Fundamentals of Microstructural Control by TMCP

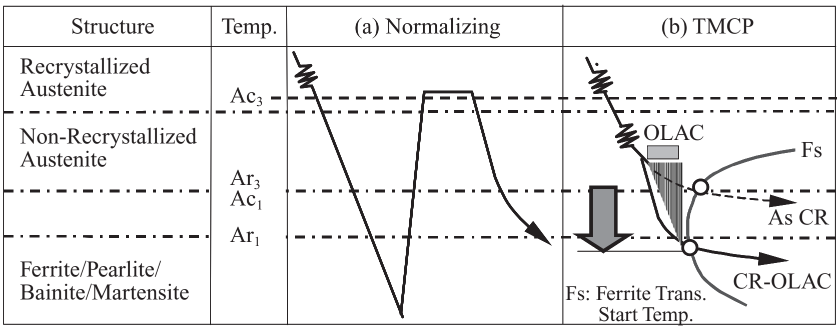
Figure 1 shows schematic diagrams of rolling and heat pattern to improve the toughness of steel plates with tensile strengths typically under 600 MPa. The toughness of the steels is improved by a off-line heat treatment at about 900°C, followed by cooling to the ambient temperature (Normalizing (Fig. 1(a)). The refined transformed structure from refined austenite contributes to the toughening effect.

In TMCP, the transformed structure is refined by a suitable combination of controlled rolling (CR) and accelerated cooling (Fig. 1(b)). To increase the nucleation sites of ferrite during cooling, CR is used to refine the grains and strain the austenite. Next, the transformed structure is further refined by accelerated cooling after CR, that is, cooling to a reduced transformation temperature at which the diffusion of the atoms is limited while the large driving force of the transformation is applied. The fine microstructure thus obtained helps realize excellent mechanical properties, such as high strength and toughness[10,11].

JFE Steel has completed the installation of three *Super*-OLAC[5] systems. The first was installed at the West Japan Works (Fukuyama) in 1998; the second, at the West Japan Works (Kurashiki) in 2003; the third, at the East Japan Works (Keihin) in 2004. With our *Super*-OLAC and HOP systems, we now have outstanding capabilities for manufacturing high-performance steel plates.

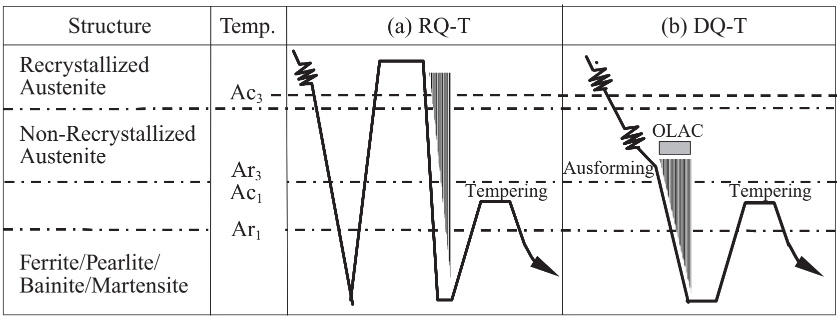
Large amounts of alloying addition are usually needed to obtain high strength in plates, especially in plates with high wall thicknesses. For this reason, the carbon equivalent (C_{eq}) of the steels tends to be increased. In steels of this type, an extremely hard martensite-austenite constituent (M-A) that compromises toughness tends to be formed in the upper-bainite structure at the HAZ of welds, especially in large-heat-input welding. To decrease the C_{eq} value via processing with *Super*-OLAC[3,4] is an important technical essence of JFE EWEL®. JFE EWEL® is applied to high-strength thick plates for container ships and building construction, plates to be welded with large heat input[3,4,12].

In conventional TMCP, accelerated cooling is usually interrupted at the intermediate temperature range, for example, at around 500°C, due to relief of internal residual stress or other factors. In producing high-strength steel plates, plates with tensile strengths typically in excess of 600 MPa, steelmakers occasionally apply direct quenching from the austenite region after hot roll-



Temp.: Temperature CR: Controlled rolling

Fig. 1 Schematic diagrams of (a) Normalizing and (b) TMCP



Temp.: Temperature RQ-T: Reheat-quenching and tempering
DQ-T: Direct quenching and tempering

Fig. 2 Schematic diagrams of (a) RQ-T and (b) DQ-T

ing down to around the ambient temperature, followed by tempering (DQ-T process (**Fig. 2**(b)). The DQ-T process is classified as a thermal refining process in some cases[1], because the process can be regarded as a rationalized combination of reheat quenching and tempering (RQ-T) (Fig. 2(a)). However, since mechanical properties of the plates are usually improved by ausforming, the DQ-T process is also classified as TMCP [1,13].

In high-strength steels produced by the DQ-T process, microstructural control of transformed structures at lower temperatures, such as bainite and martensite, is very important to obtain an excellent balance of strength and toughness. Grain refinement and straining of austenite by controlled rolling, followed by quenching to around the ambient temperature (ausforming), bring about fine sub-structures in bainite or martensite, and thus help to improve both the strength and toughness[14].

JFE Steel developed the on-line DQ-T process by introducing the *Super*-OLAC + HOP process. In the next section we explain some recent metallurgical innovations achieved by JFE Steel using *Super*-OLAC + HOP.

3. Recent Innovation in TMCP Using *Super*-OLAC and HOP

3.1 Improved Toughness of High-strength Steel Plates Produced by the DQ-T Process with *Super*-OLAC and HOP[7–9]

High-strength steels with tensile strengths of over 600 MPa produced by the DQ-T process can be further toughened by rapid tempering with HOP.

The heating rates in tempering with a conventional furnace typically range from 0.1 to 0.3°C/s (**Fig. 3**(a)). In the *Super*-OLAC + HOP process, the plates are immediately tempered after the direct quenching, at very rapid heating rates of 2 to 20°C/s (Fig. 3(b)). The heating rates in tempering by HOP are one to two orders of magnitude higher than those by conventional furnaces.

To clarify how heating rates in tempering affect the strength and toughness of steel plates produced by the DQ-T process, our group assessed the hardness and Charpy impact properties of lab scale DQ-T plates containing 0.15% of carbon, tempered at various heating rates and temperatures.

The mechanical properties of DQ-T plates, such as hardness and toughness, are usually analyzed by the tempering parameter (T.P.), based on the following equation:

$$\text{T.P.} = T \times (\log t + C) \quad \cdots\cdots\cdots\cdots (1)$$

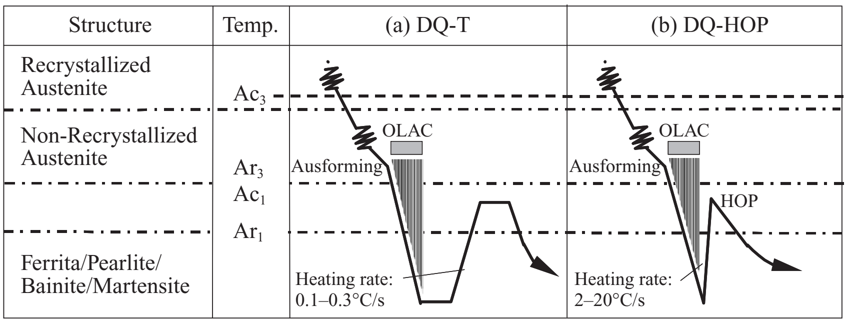
where T is the tempering temperature (K), t is the tempering time (h), and C is a constant.

The relationships between hardness, the ductile-brittle transition temperature in Charpy impact tests, and T.P. are shown in **Fig. 4**. The hardness of the DQ-T plates was determined by the T.P. without showing apparent dependency on the heating rate in tempering. It is interesting to note that the fracture appearance transition temperature (vTrs) was lowered by about 10°C at the same T.P., in the samples tempered with high heating rates of 5 to 100°C/s.

Photo 1 compares the distributions of cementite in DQ-T samples tempered by a conventional atmospheric furnace and HOP, at the same T.P. value of about 16.5 $\times 10^3$. Fine cementite particles are distributed homogeneously in the sample tempered by HOP (Photo 1(b)). Coarse cementite particles, most of them precipitated on lath boundaries of the bainite, are observed in the sample tempered by the conventional furnace (Photo 1(a)). The smaller number of coarse cementite particles is thought to contribute to the excellent toughness in plates tempered by HOP. Since strength will not be affected by this size of cementite particles, strength is independent of the heating rate in tempering.

The morphology and dispersion control technology with HOP is widely applied to JFE Steel's high-strength steels with tensile strengths of over 600 MPa, such as JFE-HITEN 610U2 and JFE-HITEN 780LE.

JFE HYD®960LE and JFE HYD®1100LE are ultra-



Temp.: Temperature DQ-T: Direct quenching and tempering
DQ-HOP: Direct quenching and HOP (Heat-treatment On-line Process)

Fig. 3 Schematic diagrams of (a) DQ-T and (b) DQ-HOP

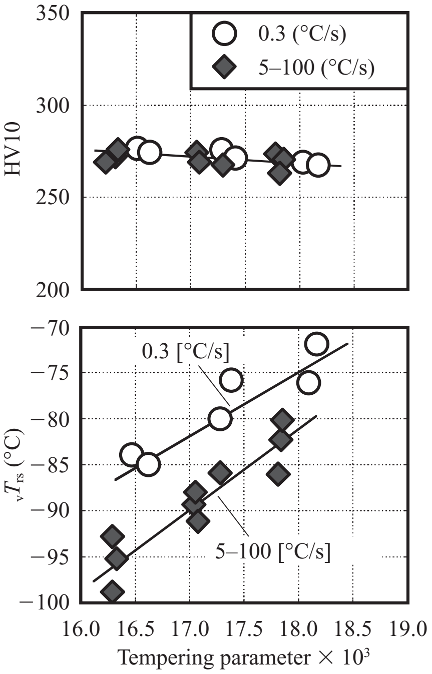


Fig. 4 Changes in Vickers hardness (HV10) and the transition temperatures by Charpy impact tests (${}_{\mathrm{v}}T_{\mathrm{rs}}$) with the tempering parameter in the TS780 MPa grade steel

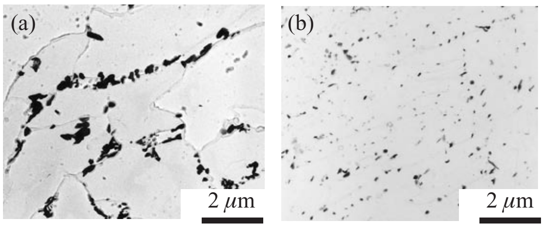


Photo 1 Cementite distributions in the TS610 MPa grade steels produced by DQ-T process; (a) Tempered with an atmospheric furnace, and (b) Tempered with HOP

high-strength steel plates with yield strengths of 960 and 1 100 MPa, respectively. The combination of ausforming with the technology for the morphological control of cementite with HOP achieves not only high strength, but also excellent low-temperature toughness and resistance to delayed fracture[16].

3.2 Microstructural Control Technology with HOP Using M-A[15,17]

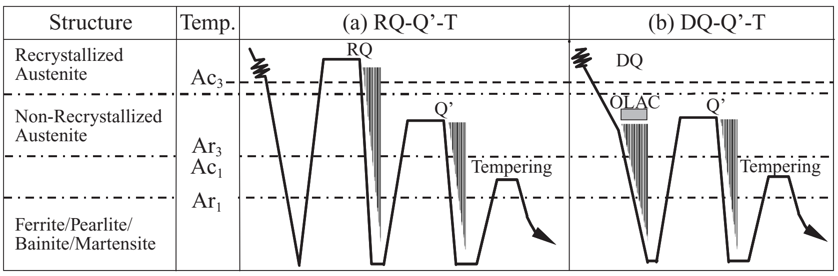
In general, steel materials are treated by a microstructural control process consisting of a soft phase, such as ferrite, and a hard phase, such as bainite or martensite, to improve uniform elongation and plastic deformability. For example, JIS (Japanese Industrial Standards) require a low yield ratio ((yield ratio) = (yield strength) / (tensile strength)) of under 80% for steel plates used for building construction (JIS G 3136), to ensure earthquake-proof properties. Thus, a microstructural control process consisting of a soft phase and hard phase is usually applied to steel plates for building construction use, through TMCP or heat treatment.

It becomes difficult, however, to obtain a low yield ratio in high-strength steel plates with tensile strengths of over 600 MPa, as the volume fraction of the low-temperature-transformed phases, such as bainite and martensite, is increased to nearly 100% through the usual quenching and tempering. Complex multiple heat treatments, such as RQ-Q'-T (reheat-quenching, intercritical reheat-quenching, and tempering (**Fig. 5**(a)) and DQ-Q'-T (direct quenching, intercritical reheat-quenching, and tempering (Fig. 5(b)), are usually conducted to obtain low yield ratios in high-strength plates of this type, sacrificing the leading time from product order to product delivery.

JFE Steel developed a new microstructural control technology using M-A (martensite-austenite constituent) as a hard phase through the *Super*-OLAC + HOP process. This technology can be used to produce high-strength steel plates with tensile strengths of over 600 MPa and low yield ratios, without any complex off-line heat treatments.

M-A compromises toughness in the heat-affected zone (HAZ) of a weld. Therefore, steelmakers must limit the amount of alloying addition, such as carbon, silicon, or aluminum, in order to suppress the formation of M-A in the usual alloy design.

To use M-A as a hard phase, it is important to obtain



Temp.: Temperature RQ-Q'-T: Reheat-quenching
Q'(Inter-critical heating and quenching), and Tempering
DQ-Q'-T: Direct-quenching
Q'(Inter-critical heating and quenching), and Tempering

Fig.5 Schematic diagrams of (a): RQ-Q'-T and (b): DQ-Q'-T

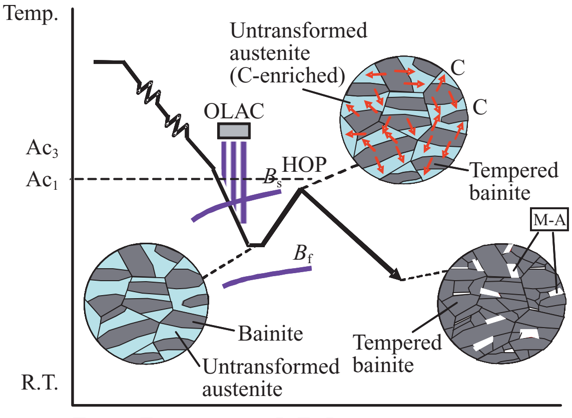
a fine and equiaxed M-A morphology through process control, and also to refine the microstructure of the matrix. An optimal combination of alloy design, ausforming, and processing, especially heat cycles after hot rolling, is essential to obtain high strength with low yield ratio and excellent toughness,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



Temp.: Temperature R.T.: Room temperature
B_s: Bainite transformation start temperature
B_f: Bainite transformation finish temperature

Fig.6 Schematic illustrations showing temperature profile and microstructural changes in the new processing with HOP

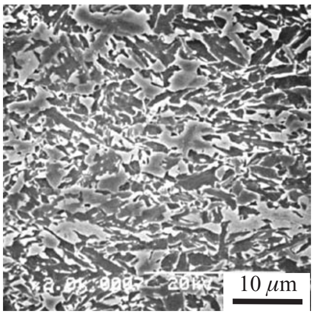


Photo 2 A scanning electron micrograph of the TS780 MPa grade steel with the low yield ratio produced by the new processing with HOP

Table 1 Typical mechanical properties of the TS780 MPa grade steel produced by the new processing with HOP

Thickness (mm)	YS (MPa)	TS (MPa)	El (%)	YR (%)	$_vE_{0°C}$ (J)
25	703	912	33	77	216

YS: Yield strength TS: Tensile strength El: Elongation
YR: Yield ratio $_vE_{0°C}$: Charpy impact energy at 0°C

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 phenomena and processing parameters are believed to further improve the various properties of steel plates.

JFE Steel continues to develop high-performance steel plates that meet customer's needs, as a pioneer of TMCP technology.

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