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Development of Thermo-Mechanical Control Process (TMCP) and High Performance Steel in JFE Steel[†]

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Abstract:

Thermo-mechanical control process (TMCP) is one of microstructural control techniques, combining controlled rolling and controlled cooling, to obtain excellent properties of steel plates, such as high strength, excellent toughness and weldability. JFE Steel has continued efforts to develop TMCP technologies, ever since JFE Steel started operation of the accelerated cooling equipment, OLAC™ (On-Line Accelerated Cooling) , in the plate mill at West Japan Works (Fukuyama) in 1980, which was the first industrial accelerated cooling system in the world. OLAC™ has continued to evolve to Super-OLAC™ and Super-OLAC™-A, in 1998 and 2011. In 2004, HOP™ (Heat-treatment On-line Process) was also installed in the plate mill at Fukuyama. Super-CR enabling quite unique cooling patterns during controlled rolling has also installed at East Japan Works (Keihin) in 2009. This paper describes features of those leading facilities and the recent development in TMCP with some examples of new products in JFE Steel.

1. Introduction

In response to progress in design/manufacturing technologies for welded structures and requirements for total cost reduction, higher strength and high weldability are constantly demanded in the steel plates used in those structures. In addition, the scale of structures has increased and service environments have become more severe in recent years, and at the same time, there is a tendency to attach importance to safety and security in building design. Thus, both higher and more complex performance requirements are now placed on steel plates. To satisfy these performance requirements, detailed material design technology and advanced manufacturing technology are essential.

Higher performance in steel plates has been supported by alloy design technology and untiring progress in the thermo-mechanical control process (TMCP). It can also be said that the progress of TCMP is the result of the pursuing continuation of the rolling and water cooling processes and development of on-line systems for those processes. Controlled rolling and controlled cooling make it possible to satisfy high strength and high toughness requirements which could only be achieved conventionally by off-line heat treatment. Since JFE Steel applied the on-line accelerated cooling device OLAC™ (On-Line Accelerated Cooling) to an industrial plate mill, which was the world's first practical application of this technology, the company has worked to obtain higher performance in cooling equipment through tireless technological development[1, 2)]. JFE Steel has also achieved continuation of the tempering process by HOP™ (Heat-treatment On-line Process), realizing on-line production of higher strength steel plates. In addition, JFE Steel proposed a new concept of continuation of controlled rolling and water cooling, and applied *Super*-CR, which is intensive cooling equipment located close to the mill, to a practical operation[3)]. This type of process continuation also responds to the needs of higher productivity and shorter production time that are always demanded in industrial products.

On the other hand, improved weldability is required in steel plates for welded structures. The problems of

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reduced low temperature crack resistance of the weld and deterioration of the toughness of the heat affected zone (HAZ) accompanying higher strength were solved by achieving high strength with a low alloy composition design with TMCP. Moreover, the performance of plates for large heat input welding was greatly improved by progress in precipitate and inclusion control technologies, but the basis of this was low alloy design preconditioned on TMCP after all.

This paper reviews the development of plate manufacturing technology at JFE Steel, focusing on technical innovations in TMCP, and also presents an outline of the features of high performance steel plates, which were developed by making the maximum possible use of these process technologies and are used in diverse fields.

2. Development of TMCP Technologies of JFE Steel

2.1 On-line Accelerated Cooling Device: *Super*-OLAC™

Together with controlled rolling, accelerated cooling is a core technology of TMCP. In 1980, JFE Steel applied an on-line accelerated cooling device (OLAC™) for plates in an industrial operation at West Japan Works (Fukuyama) for the first time in the world, and since then, has continued its efforts to achieve high performance in accelerated cooling technology.

Subsequently, JFE Steel developed *Super*-OLAC™,[1] in which accelerated cooling was realized by a high cooling rate equivalent to the theoretical limit by a unique JFE Steel's water flow control technology. The first *Super*-OLAC™ was put into operation at West Japan Works (Fukuyama) in 1998. In the conventional water cooling method, a transitional boiling consisting of mixed nuclear boiling and film boiling occurs. This causes unstable cooling, and temperature deviation increases as cooling proceeds, resulting in non uniform of mechanical properties. In *Super*-OLAC™, JFE Steel pursued cooling by nuclear boiling over the entire plate surface. Together with achieving uniform cooling by stable cooling, this also realized a high cooling rate. These features have dramatically improved the quality of TMCP steels[2].

Deployment of *Super*-OLAC™ to three plate mills was finished with startup of units at West Japan Works (Kurashiki) in 2003 and East Japan Works (Keihin) in 2004, completing a system which enables the maximum use of TMCP. In 2011, *Super*-OLAC™-A was introduced at Fukuyama. This is a further evolution of the *Super*-OLAC™ technology responding to the more sophisticated property requirements of recent years.

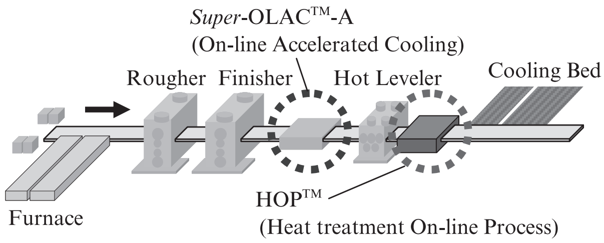

Fig. 1 Layout of on-line accelerated cooling and heat-treatment facilities in West Japan Works (Fukuyama)

2.2 Heat-Treatment On-Line Process: HOP™

Conventionally, quenched and tempered steel was produced by applying heat treatment equipment which was separated from the mill line. To achieve higher efficiency by developing an on-line system instead of the conventional off-line process, HOP™ was introduced in the downstream of the *Super*-OLAC™ at West Japan Works (Fukuyama) and was put into operation in 2004[2].

HOP™ is an induction heating system, in which a steel plate is heated by Jule heating due to induced eddy current. A longitudinal flux type electromagnetic coils are used as inductors. Regarding the heat generation in plates, uniform and highly accurate temperature control is achieved by precisely controlling the electric power input. The layout of the equipment is shown in **Fig. 1**. HOP™ was designed as an integrated heating process, in which the heating device is arranged immediately after the hot leveler in order to improve heating efficiency by utilizing the sensible heat of the plate after accelerated cooling effectively.

In the past, high tensile strength products with tensile strength of 600 MPa and higher had been produced mainly by quenching and tempering in off-line processes. By enabling on-line production, HOP™ has realized an increase of productivity and a large reduction of lead time. At the same time, it has also been found that toughness is particularly improved in comparison with off-line tempering products because the carbides that are formed in the tempering process are both uniform and fine grained as a result of the rapid heating which is only possible with induction heating[4]. By coupling the HOP™ technology with the excellent temperature control performance of *Super*-OLAC™, it has become possible to perform reheating immediately after stopping water cooling, which had been impossible with conventional TMCP. A new microstructure control technology was developed based on this concept and has been applied to high tensile strength products with distinctive features[5, 6].

2.3 Intensive Cooling Equipment Close to Mill: *Super*-CR

Controlled rolling is a technology in which strength is increased by applying plastic deformation in the noncrystallization temperature range of austenite in order to accumulate dislocations, and forming transformation nucleation sites not only at the grain boundaries but also within the grains. Controlled rolling was applied to actual production from an earlier date than controlled cooling[7].

When manufacturing controlled rolling products, the finish rolling temperature is set lower than that for conventional rolled products. This means waiting time for temperature adjustment is frequently necessary during the rolling process, and the waiting time tends to become longer with thicker products. Cooling by supplying a shower of water to plates has been used to shorten cooling waiting time, but much time was required to transfer the plates, to perform water cooling, and to confirm by measurement with a pyrometer the desired temperature drop had been achieved after heat recovery at the surface. The loss of time in these processes made the lower production efficiency of controlled rolling products in comparison with conventional products. In addition, the cooling rate was limited by the low water flow rate, and remaining water on the upper plate surface caused overcooling. Thus, the difficulty of achieving uniform cooling of the entire plate had been pointed out as a main problem[3].

To overcome this problem, and to realize high performance TMCP by combining controlled rolling and cooling, JFE Steel introduced *Super*-CR (Super-Controlled Rolling) as the world's first intensive rapid-cooling equipment close to the mill. *Super*-CR was introduced at East Japan Works (Keihin) and was started up in 2009.

Figure 2 shows the layout of the equipment. *Super*-CR is a intensive cooling device which is installed in close proximity to the rolling mill, and makes it possible to perform rolling and water cooling simultaneously for the first time in the history of controlled rolling. By applying water cooling with an extremely high water flow rate in multiple passes, a cumulative cooling effect is obtained and high efficiency of production is successfully realized. A water cooling technology which enables uniform and high speed cooling of the entire steel plate was established by applying a special water flow control technique. Temperature control is performed by accurately measuring the plate temperature on-line during operation, and obtaining the optimum number of cooling passes and rolling speed corresponding to the required temperature drop. To prevent warping during rolling, the temperature difference between the top and bottom sides of the plate is controlled to within the proper range at all times. The establishment of this *Super*-CR technology has dramatically improved the rolling efficiency of controlled rolling products, and has also increased JFE Steel's production capacity for TMCP high strength steel. Cumulative production since start-up of *Super*-CR now exceeds 1.5 million tons.

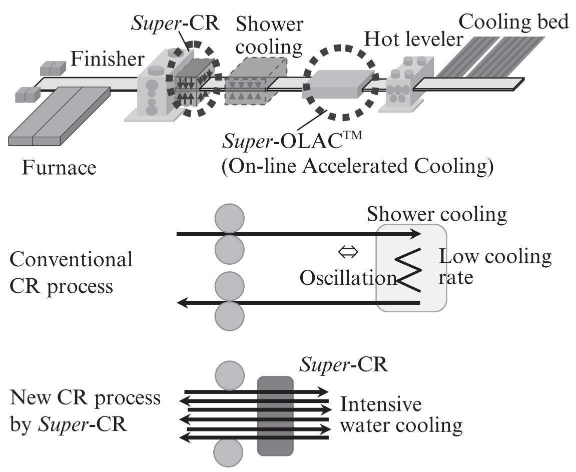

Fig. 2 Layout of plate mill of East Japan Works (Keihin) and new controlled rolling process by *Super*-CR

Combining *Super*-CR and the accelerated cooling device *Super*-OLAC™ has also made it possible to apply 2-step cooling for the first time, and thus has increased the flexibility in TMCP. Application to the manufacture of high strength steel plates with higher deformation characteristics than the conventional products for shipbuilding, construction, pipe material, etc. and improvement of scale adhesion by control of the surface temperature are among the expected effects of this technology.

3. Development of High Performance Steel Plates

3.1 Steel Plates for Shipbuilding

The development of higher strength steel plates for shipbuilding is the history of the development of TMCP. By the commercialization of the initial stage of TMCP, YP390 MPa class steel plates were applied practically during the 1980s and contributed to weight reduction in ships. Simultaneously with this, higher strength characteristic was realized by a low carbon equivalent (Ceq) composition design, enabling application of large heat input welding. This made an important contribution to higher efficiency in ship construction.

Recent years have seen heightened needs for higher efficiency in marine transportation, reduction of fuel consumption, and reduction of environmental loads. Responding to these needs, great progress has been made in steel plates for shipbuilding and their application technologies. As the upscaling of container ships tends to encourage the use of thicker steel materials, this created the need for even higher strength steels in order to reduce ship weight. For this, the development of

YP460 MPa class steel exceeding the strength of YP390 MPa class steel was desired. Moreover, the quality requirements of welds produced by large heat input welding must also be satisfied because electrogas arc welding (EGW), which is a high efficiency vertical welding method, is applied in welding the heavy gauge materials of container ships.

From the viewpoint of safety against brittle fracture of the steel materials and welded structures, brittle crack arrest toughness is also demanded in the strength decks of large-scale container ships using ultra-heavy steel plates with thicknesses exceeding 50 mm. This type of YP460 MPa steel for use in container ships must meet high and complex property requirements, which include strength together with suitability for large heat input welding and brittle crack arrest toughness.

JFE Steel deepened its EWEL™ technology[8, 9] and developed and applied a YP460 MPa class steel[10] that satisfies both high strength and high quality in large heat input welding joints. By applying *Super*-OLAC™, which is one of the important basic technical elements of the EWEL™ technology, outstanding toughness was achieved in large heat input welding welds by reduction of Ceq, further improvement of microalloying technology, minimization of the width of the coarse grain HAZ, and refinement of the microstructure.

A manufacturing technology for steel plates with high brittle crack arrest toughness, even in ultra-heavy steel plates with thicknesses of more than 60 mm, was established by high performance controlled rolling. The chemical composition, mechanical properties, and examples of EGW joint properties of the developed YP460 MPa class steel for shipbuilding are shown in **Table 1**, **Table 2**, and **Fig. 3**, respectively. The developed steel satisfies high strength, as well as shipbuilding E grade low temperature toughness of the base metal and low temperature toughness of large heat input welding joints.

To meet the advanced, complex needs of the heavy thickness steel plates used in container ships, JFE Steel has established a production system for large heat input welding specification, high brittle crack arrest toughness specification products for heavy thickness plates of YP355 to YP460 MPa class steels[11, 12].

3.2 Steel Plates for Building Structures

The high-rise buildings of recent years are characterized by longer spans and more complex structures. High strength, heavy steel plates are required for these applications. From the viewpoint of earthquake resistance requirements, there is also a heightened need for high performance steel materials which have a low yield ratio ((Yield point) / (Tensile strength)), high toughness, and good weldability for building structures fabrication.

JFE Steel has developed and commercialized the HBL™ Series of TMCP-type low yield ratio, high tensile strength steels with an excellent earthquake resistance property for building structures in a wide range of strength grades and plate thicknesses. **Table 3** shows the product lineup.

JFE Steel developed HBL™ 385 as a tensile strength of 550 MPa class TMCP steel with an excellent balance of economy, earthquake resistance property, and weldability, and led the industry in obtaining approval by Japan's Minister of Land, Infrastructure, Transport and Tourism in 2002. In HBL™ 385, a yield ratio of 80% or

Table 1 Chemical compositions of YP460 MPa class steel plate

Grade	Thickness (mm)	Chemical composition (mass%)						
		C	Si	Mn	Nb	Ti	Others	Ceq*
YP460	60	0.05	0.07	1.55	0.01	0.01	Cu, Ni, Ca, B, etc.	0.39

*Ceq = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15

Table 2 Mechanical Properties of YP460 MPa class steel plate

Grade	YP (MPa)	TS (MPa)	El (%)	vE_{-40} (J)
YP460	508	654	21	282

YP: Yield point TS: Tensile strength
El: Elongation vE: Absorbed energy

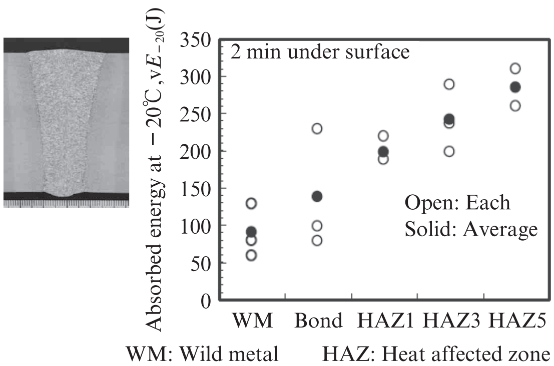

Fig. 3 Charpy impact properties of electrogas arc welding (EGW) welded joint of YP460 MPa class steel plate

Table 3 Lineup of thermo-mechanical control process (TMCP) steel plate HBL™ for building structure

Grade	Thickness (mm)	YS (MPa)	TS (MPa)	YR (%)	vE_0 (J)
HBL™ 325	40≦*t*≦100	325–445	490–610	≦80	≧27
HBL™ 355	40≦*t*≦100	355–475	520–640	≦80	≧27
HBL™ 385L HBL™ 385	12≦*t*≦ 19 19≦*t*≦100	385–505	550–670	≦80	≧70
HBL™ 440	19≦*t*≦100	440–540	590–740	≦80	≧70
HBL™ 630L	12≦*t*≦ 40	630–750	780–930	≦85	≧70

YS: Yield strength TS: Tensile strength
YR: Yield ratio vE: Absorbed energy

less and standard strength of 385 MPa were realized while maintaining the same weldability as the conventional 520 MPa class TMCP steel (Standard strength level: 355 MPa) by utilizing high accuracy TMCP technology making full use of *Super*-OLAC™.[13, 14]

SA440 (Tensile strength: 590 MPa) was conventionally manufactured by multiple off-line heat treatment processes. JFE Steel established a technology for on-line production of steel with the same mechanical properties as SA440 and completed commercialization as HBL™ 440. This product was developed and applied practically as a result high-accuracy of controlled rolling conditions and the excellent temperature control of *Super*-OLAC™.[15, 16]

High strength steel plates for building structures are frequently used in box section columns, and high efficiency submerged arc welding (SAW) or electro-slag welding (ESW) is applied in their assembly. Since these welding methods are large heat input welding processes, with heat input of 600 kJ/cm in SAW and a maximum of 1 000 kJ/cm in ESW, the toughness of the HAZ displays remarkable deterioration if steel materials are used without special countermeasures, and the earthquake resistance property of high-rise buildings is reduced. JFE Steel commercialized high HAZ toughness steels in grades HBL™ 325 to HBL™ 440 by applying the JFE EWEL™ technology for improvement of HAZ quality in large heat input welding[9].

Likewise, JFE Steel also achieved on-line production in the manufacture of low yield ratio 780 MPa class steel, even though use of multiple off-line heat treatment processes had been considered indispensable[6]. In HBL™ 630L, excellent mechanical properties of the base metal and outstanding weldability and weld toughness are achieved by forming a multiphase microstructure, which consists of a bainite main phase and fine M-A (Martensite-austenite constituent), by applying TMCP and HOP™ (**Fig. 4**). HBL™ 630L was recently adopted as the steel material for the welded box section columns of Shinjuku Toho Building, and approximately 250 tons were used.

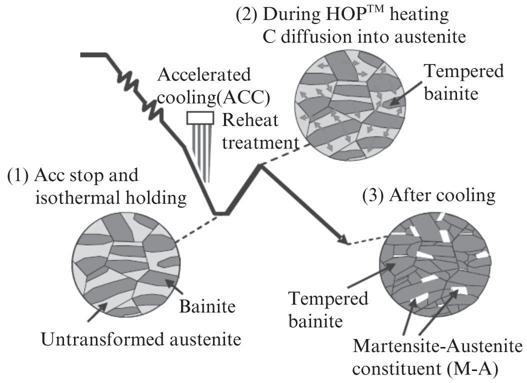

Fig. 4 Schematic illustration of microstructure change by HOP™ for dual phase microstructural control

3.3 Steel Plates for Construction/Industrial Machinery

High strength and ultra-high strength steels are actively used in construction/industrial machinery, as there is a strong need for weight reduction in this field. With service environments becoming increasingly severe, low temperature toughness is also demanded. However, since high strength and improved toughness are mutually contradictory properties, special manufacturing technology is necessary in order to satisfy both requirements.

JFE Steel developed and commercialized ultra-high strength steel plates with excellent low temperature toughness for use in construction/industrial machinery by making the fullest possible use of controlled rolling technology and the continuous *Super*-OLAC™ and HOP™ process[17]. The conventional heat treatment process for high strength steel is reheating, quenching, and tempering. However, application of this continuous process has made it possible to reduce contents of alloying elements and satisfy both high strength and low temperature toughness, while also increasing JFE Steel's supply capacity and shortening the production period.

In these plates, high strength is achieved by direct quenching (ausforming) from work-hardened austenite by controlled rolling, and the low temperature toughness improvement effect of tempering by using HOP™ is utilized. In comparison with the conventional off-line heat treatment, the heating rate in heating by HOP™ is 1–2 orders of magnitude faster. As a result, cementite precipitates finely and uniformly, and this has the effect of improving toughness. As shown in **Fig. 5**, this microstructure control realizes steel with excellent low temperature toughness, high resistance to delayed fracture, which is critical in the practical application of ultra-high strength steels, and outstanding weldability thanks to a low alloy composition design.

JFE Steel supplies a number of products with distinc-

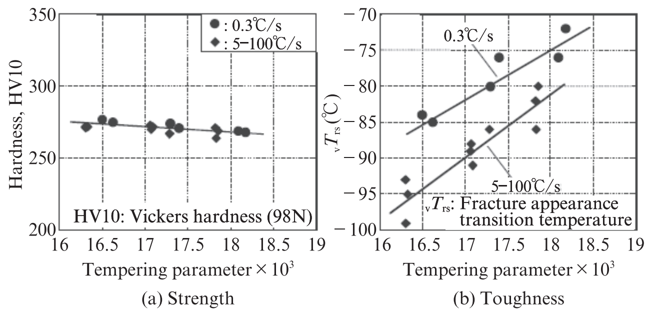

Fig. 5 Relationship between tempering parameter and mechanical properties of TS780 MPa class steel

tive features, such as JFE-HITEN 780LE, HYD™ 960LE, and HYD™ 1100LE, by applying the carbide morphology control technology and material quality control technology by HOP™.

3.4 Steel Plates for Energy Applications

Steel plates play a key role in plant structures related to the development, production, transportation, and use of energy resources. What is required in these plants is reduction of construction cost and running costs, and one of means to reduce costs is use of high strength materials. High strength materials make it possible to increase the scale of the facilities and to operate under higher pressure and high temperature conditions. At the same time, it is also possible to reduce the amount of materials used, and as a result, the weight of the equipment and the amount of construction work can also be reduced.

On the other hand, because these plants handle petroleum and natural gas, which have high energy densities, a high order of safety and reliability is demanded in the materials. This is not limited simply to securing adequate safety in the design conditions; it is also necessary to ensure adequate safety against external factors such as natural disasters, corrosion, etc.

Severe low temperature toughness requirements are applied to plates which are to be used in drilling rigs and platforms for extremely cold environments. In addition to EH36, FH36, etc., which are high strength steel plates under the specification of ship's classification, TMCP-type high tensile strength steels represented by API 2W 50 (Yield point: 355 MPa or higher) and 60 (410 MPa or higher) are used in production platforms, beginning with jackets and also including the top side and pile of the tension leg platform (TLP) and the top side of SPAR. In addition, the crack tip opening displacement (CTOD) property, which is used in a severe fracture mechanics approach, is required in welded joints of these plates.

JFE Steel has realized practical application of plates which amply satisfy these property requirements by advanced material quality design and steelmaking technologies utilizing microalloying technology, together with state-of-the-art controlled rolling/controlled cooling technology using the on-line accelerated cooling device *Super*-OLAC™. In addition to satisfying both a low weld crack sensitivity composition (P_{CM}) having excellent welding and base plate properties in heavy gauge materials, welded joint toughness and the CTOD property have also been improved by microstructure refinement by using Ca nonmetallic inclusions[18, 19].

Ultra-low temperature specification yield strength 690 MPa class ultra-heavy steel plates are used in the rack and chord materials of jack-up rigs. JFE Steel has established a manufacturing technology for high quality plates by a unique manufacturing process in these heat treated-type severe specification ultra-heavy gauge plates[20], and has numerous actual production results. **Table 4** shows examples of the steel plates developed by JFE Steel for use in offshore structures.

Table 4 Available strength and thickness of steel plates for offshore structures

YP Class (MPa)	Charpy temp. (°C)	CTOD Test temp. (°C)	Thickness (mm)
355	−40	−10	≦101.6
420	−40	−10	≦101.6
	−60	−40	≦ 76.4
500	−40	—	≦108
550	−40	—	≦108
620	−40	—	≦108
690	−40	—	≦180

YP: Yield point CTOD: Crack tip opening displacement

4. Conclusion

This paper has introduced the basic technologies of JFE Steel's state-of-the-art TMCP equipment, including *Super*-OLAC™, *Super*-OLAC™-A, and HOP™, as well as *Super*-CR, which enables a new type of material quality control by combining high efficiency controlled rolling and the *Super*-OLAC™ technology. It has also presented overviews of several high performance, high tensile strength products that were developed by utilizing these world-leading facilities and combining steelmaking technology and metallurgical phenomena.

In the future, JFE Steel will continue to develop TMCP that organically links metallurgical phenomena and process development, and will respond to the needs of customers by developing more advanced manufacturing technologies, while also powerfully promoting the development of new plate products that contribute to society.

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