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JFE Steel's Advanced Manufacturing Technologies for High Performance Steel Plates†

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Abstract:

To meet the requirements of higher strength, improved weldability, and higher performance placed on structural steel plates for large-scale structures in recent years while also reducing manufacturing costs, JFE Steel has developed revolutionary plate manufacturing technologies; the Super-OLAC, a next-generation accelerated cooling technology for plates with a high cooling capacity, achieving the theoretical cooling limit, and uniform cooling performance, and the HOP (heat-treatment on-line process), an induction heating-type on-line heat-treatment process which reduces delivery times. Making full use of these plate manufacturing technologies, JFE Steel has developed high quality, high performance plates for a wide range of fields.

1. Introduction

Although the performance requirements placed on steel plates in recent years differ to some extent depending on the application and field, against the background of more advanced design and manufacturing technologies for final products and structures and the need for total cost reduction, these requirements have become increasingly severe. Concretely, performance requirements cover a diverse range, including higher strength, improved weldability, and higher performance. To satisfy these requirements, precise material design technology and advanced manufacturing technology are essential.

Based on this background, JFE Steel was among the first steel makers to begin development of the thermo-mechanical control process (TMCP) with water quenching as the core technology as a manufacturing technology for high strength, high toughness steels with excellent weldability. This paper describes the plate manufacturing technologies developed and applied by JFE Steel in recent years include the *Super*-OLAC, a new accelerated cooling technology for plates, and the HOP (heat-treatment on-line process), an on-line heat-treatment process after accelerated cooling. This paper also explains the manufacturing process for Easyfab® steel plate, in which residual stress in plates is reduced to virtually zero by applying a cold leveler with new functions, while also applying these advanced TMCP technologies. High-performance plates created with these processes are also introduced by field of application.

2. Development of New Accelerated Cooling Technology "*Super*-OLAC"

Together with controlled rolling, accelerated cooling is the core technology in TMCP (thermo-mechanical control process) technology[1)]. JFE Steel began development of accelerated cooling before other steel makers and succeeded in practical application of the world's first on-line accelerated cooling process for plates, called OLAC® (on-line accelerated cooling) in 1980[2)].

At the beginning of the 1990s, TMCP steel manufactured using accelerated cooling realized high strength and dramatically improved weldability, contributing to rationalization in the construction of welded structures and improved safety in a wide range of fields, beginning with shipbuilding. However, in recent years, increasingly strict quality requirements, such as reduced strength deviation, have also been applied to steel plates. To meet these needs, JFE Steel carried out basic research to achieve a fundamental solution to the problems associated with conventional cooling and developed a next-

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generation accelerated cooling process called the *Super*-OLAC (**Photo 1**) based on a completely new concept. In 1998, the first *Super*-OLAC was applied in a commercial production line at JFE Steel's West Japan Works Fukuyama District Plate Rolling Plant[3)].

The heat transfer and boiling phenomena which occur when steel plates are water-quenched can be broadly classified into two modes, nucleate boiling and film boiling (**Fig. 1**). In nucleate boiling, the cooling water is in direct contact with the steel, and heat is transferred by generation of bubbles. In contrast, in film boiling, a film of steam forms between the steel and the cooling water, and heat is transferred through this steam film. Nucleate boiling has a higher cooling capacity. At the start of plate cooling, the surface temperature is high and film boiling is predominant. However, as the surface temperature decreases, the steam film becomes unstable, the cooling water begins to come into direct contact with the plate locally, and boiling gradually shifts to nucleate boiling. Moreover, in the transient boiling condition, when film boiling and nucleate boiling coexist, the cooling capacity characteristically increases as cooling proceeds. This means that any temperature differences which existed before cooling are exaggerated as the cooling process proceeds.

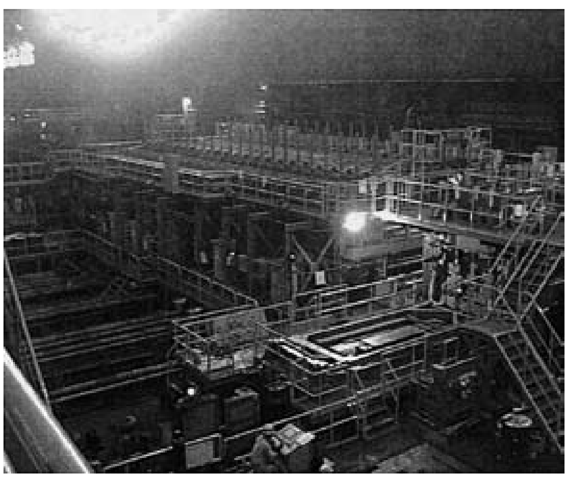

Photo 1 *Super*-OLAC at Fukuyama District, West Japan Works

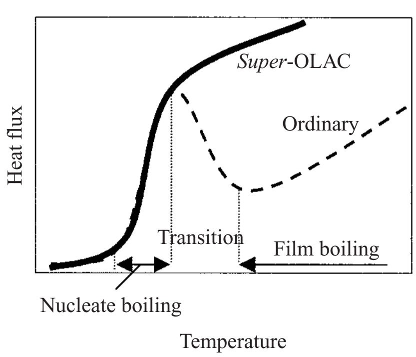

Fig. 1 Boiling curve of *Super*-OLAC

With conventional cooling methods such as spray cooling or laminar cooling, if the cooling water flow rate is increased to strengthen cooling, cooling rapidly shifts to transient boiling, consisting of mixed nucleate boiling and film boiling. As a result, cooling becomes unstable and temperature deviations increase as cooling proceeds, causing the problem of unstable plate quality (**Fig. 2**).

To solve this problem, in the *Super*-OLAC, JFE Steel investigated a cooling method which avoids transient boiling and achieves a nucleate boiling over the entire plate surface virtually simultaneously with the start of cooling. Based on the results of this study, for cooling of the top side of the plate, a method was adopted in which the cooling water flows in one direction, in the direction of plate movement, from nozzles located in close proximity to the plate (corridor flow cooling), while cooling of the bottom side is performed by spraying cooling water from nozzles densely arranged in the water tank, and cooling the plate with the entrained flow (induced laminar flow cooling). This cooling method realized nucleate boiling with a high cooling capacity on both the top and bottom sides of the plate. With plate thicknesses of 30 mm and over, the method realized a high cooling rate substantially equal to the theoretical limit cooling rate[4)] shown by Eq. (1), in which diffusion of heat from the interior of the steel is rate-determining (**Fig. 3**).

$$\frac{T(x,t)-T_0}{T_1-T_0} = \frac{4}{\pi}\sum_{i=1}^{\infty}\frac{1}{2i-1}\sin\left\{\frac{(2i-1)\pi x}{s}\right\}\exp\left\{-\frac{(2i-1)^2\pi^2\alpha t}{s^2}\right\} \quad \cdots\cdots (1)$$

T : Temperature
T_1 : Initial temperature
T_0 : Coolant temperature
s : Thickness
α : Thermal diffusivity

This rapid cooling is 2–5 times faster than conven-

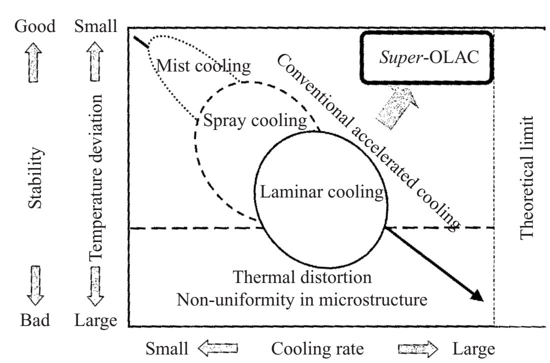

Fig. 2 Cooling rate and temperature uniformity

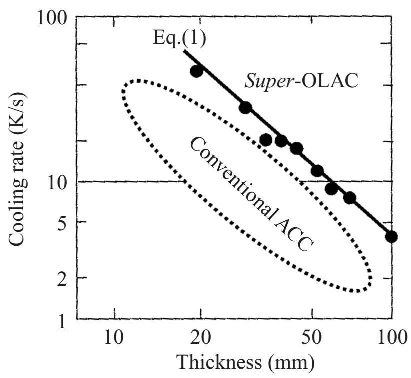

Fig. 3 Cooling rate of *Super*-OLAC

tional accelerated cooling. Moreover, the surface temperature distribution in the plate (plane) after the *Super*-OLAC shows uniformity equal to that of as-rolled steel plates, with which accelerated cooling is not performed.

Cumulative production of accelerated cooling steel plates using the *Super*-OLAC exceeded 3 million tons in the first 5 years after startup. The No. 2 unit of *Super*-OLAC was started up at JFE Steel's West Japan Works Kurashiki District Plate Rolling Plant in May 2003, followed by No. 3 unit at the East Japan Works Keihin District Plate Rolling Plant in July 2004. Thus, all three of JFE Steel's plate mills are now equipped with state-of-the-art accelerated cooling equipment. It should also be noted that this new accelerated cooling technology, *Super*-OLAC, received the Iwatani Naoji Memorial Award and Okochi Memorial Technology Award in 2002, the Special Award of the Japan Industrial Technology Review Committee in 2003, and the National Invention Award in 2004.

3. New On-Line Heat Treatment Process "HOP"

To date, manufacture of quenched and tempered steel plates has been performed off-line using heat treatment equipment separated from the rolling line. To improve efficiency by performing this off-line treatment as an on-line process, an on-line heat treatment process called HOP (heat-treatment on-line process) was installed and put into operation at the West Japan Works Fukuyama District Plate Rolling Plant.

JFE Steel previously developed induction heating equipment for rough bars with a width of 2 m, which is applied before the finishing rolling line in hot rolling[5]. However, it was necessary to develop an unprecedented new large-scale induction heating power source for use in heating steel plates with widths of 4.5 m. The technology, in which multiple units of the newly-developed high frequency power source are operated synchronously in parallel, was a breakthrough which realized induction heating of steel plates for the first time in the world.

The newly-developed HOP is an induction heating method in which heating is performed using the heat generated when an induced electric current is passed through a steel plate using an electromagnetic coil (inductor). From the viewpoints of heating efficiency and simplicity of the equipment, a solenoid-type electromagnetic coil was adopted. Although heat is generated in the interior of the plate, the amount of heat can be strictly controlled by the input power. Converting the heat generated by induction heating was converted to heat flux in the case of gas heating for convenience, it could be understood from experience that heating equivalent to a heat flux of approximately 10^5–10^7 W/m² is possible[5,6]. This value is roughly 100 times larger than that in gas heating, and makes it possible to realize heating with an extremely large energy density.

The equipment layout is shown in **Fig. 4**. The HOP is installed immediately after the hot leveler. This arrangement was adopted to improve heating efficiency by effectively utilizing the sensible heat of the plate after the *Super*-OLAC. Thus, the HOP was designed as an integrated heating process with the inductor installed in close proximity to the hot leveler.

The HOP has the following two features.

(1) Realizes Complete On-Line Heat Treatment Synchronized to Rolling

Establishment of a total on-line process for rolling–accelerated cooling–heat treatment realized mass production and made it possible to meet extremely short delivery schedules.

(2) Enables Microstructural Control of New Steel Plates

Combining the HOP with the *Super*-OLAC accelerated cooling device enabled free control of phase transformation and control of carbide and nitride precipitation (**Fig. 5**).

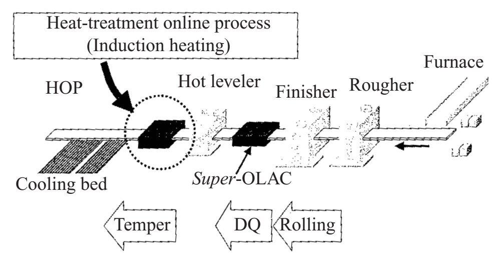

Fig. 4 Layout of on-line heat-treatment facilities

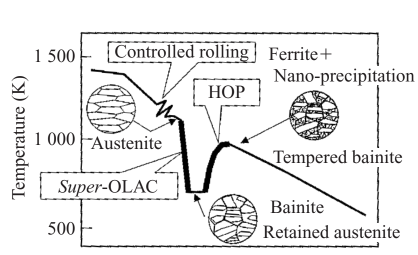

Fig. 5 JFE Steel's on-line heat-treatment process

High expectations are placed on the HOP, which takes advantage of the outstanding features of induction heating, as a new process for plates aimed at the development of innovative new products in the future.

4. Multi-functional Steel Plate with Excellent Workability "Easyfab®"

Particularly in the fields of shipbuilding, architectural construction, and bridges, steel plate products are used as assembly components after cutting to various component shapes. However, in recent years, increasingly strict requirements have been placed on ease of use. JFE Steel therefore commercialized a new multi-functional steel plate with excellent workability, "Easyfab®," which features less deformation in cutting, high efficiency in assembly, and excellent weldability, with the additional function of longer fatigue life, utilizing the excellent cooling control characteristics of the *Super*-OLAC (**Fig. 6**). This chapter describes a residual stress control technology for imparting excellent cutting performance, which is one function of "Easyfab®."

4.1 Residual Stress Control Technology Using *Super*-OLAC

Residual stress generated in steel plates is mainly caused by the temperature distribution in the plate at the end point of rolling (accelerated cooling). When a steel plate with a temperature distribution is cooled to room temperature, non-uniform heat contraction occurs, depending on the position. This non-uniform heat contraction generates residual stress. With conventional accelerated cooling technologies, the temperature deviation immediately after cooling stop was large, and this caused large deviations in residual stress, both in individual plates and between plates. As a result, there were also deviations in the amount of deformation during cutting. As an accelerated cooling technology with excellent cooling uniformity, the *Super*-OLAC achieves uniformity in the temperature immediately after cooling stop, and has reduced the residual stress in TMCP plates to the level of as-rolled (non-water cooled) materials.

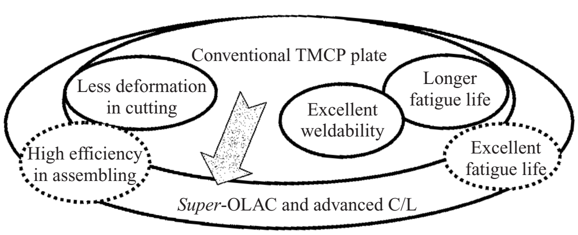

Fig. 6 Concept of "Easyfab®"

4.2 Cold Leveler with New Functions and Development to Ultra-low Residual Stress Plates

The cold leveler (C/L) is employed to correct the flatness of steel plates in a process called leveling. By also using the C/L function of imparting uniform large strain over the full width of the plate, in combination with uniform cooling by the *Super*-OLAC, it is possible to produce plates with extremely low residual stress. The concept of residual stress control by the C/L is shown in **Fig. 7**. Residual stress after leveling decreases as bending strain at the C/L increases (dotted line in figure: conventional accelerated cooling; solid line: *Super*-OLAC). Furthermore, with *Super*-OLAC products, which are characterized by low residual stress before the C/L in comparison with conventional accelerated cooling materials, the ultra-low residual stress region can be achieved with a smaller C/L bending strain. In Oct. 2003, JFE Steel added the following new functions to the C/L at the West Japan Works Kurashiki District Plate Rolling Plant with the aims of expanding the leveling capacity and manufacturing ultra-low residual stress steel plates (**Fig. 8**).

(1) Vertical Flexure Compensation by Hydraulic Dynamic Control (Hydraulic Stretch Compensation)

The amount of elastic deformation of the leveler is calculated from the measured load during leveling, and vertical flexure (stretch) compensation is performed by dynamic correction of the screw down position.

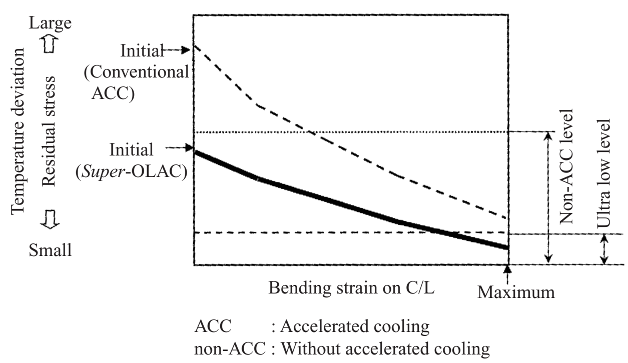

Fig. 7 Residual stress controlled by *super*-OLAC and C/L

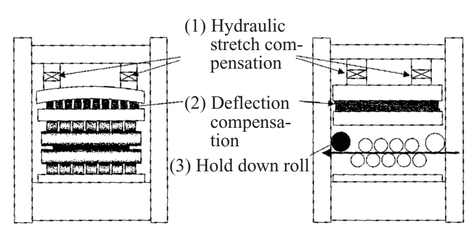

Fig. 8 Schematic diagram of advancement in the C/L

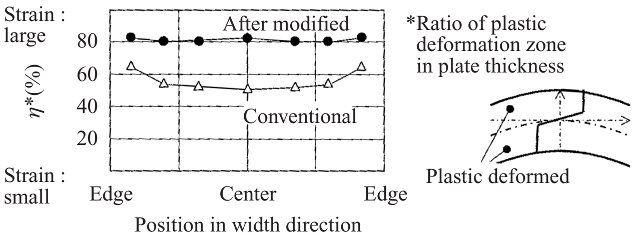

Fig. 9 Distribution of bending strain in width direction

(2) Horizontal Flexure Compensation by Wedge Control (Deflection Compensation)

Flexure of the leveling rolls is calculated, and horizontal flexure (deflection) compensation is performed by adjusting screw down to be uniform in the plate width direction using wedges.

(3) Intermesh Control by a Hold Down Roll

An intermesh control function using a hold down roll was introduced to compensate for reduced screw down accuracy due to roll wear, etc.

Figure 9 shows the distribution of maximum bending strain in the plate width direction when plates with an attached strain gauge were leveled with the C/L with new functions. The new functions make it possible to impart large bending strain uniformly across the full width, establishing a uniform heavy reduction leveling technology for wide materials with the largest width in the world (5 350 mm).

As described above, by utilizing the uniform cooling capacity of the *Super*-OLAC, the new functions of the improved C/L can be employed extremely effectively, and production of steel plates with extremely low residual stress is possible.

5. New Products Manufactured Using Innovative Processes

5.1 Steel Products for Shipbuilding

With the recent trend toward large-scale container ships, heavy gauge, high strength steel plates are increasingly adopted, requiring ultra-large heat input in welding. Because this causes coarsening of the HAZ microstructure, securing low temperature toughness has become a problem. To meet this need, JFE Steel produces heavy gauge, high strength steel plates with no reduction in weldability at the same carbon equivalent (C_{eq}) as conventional steels by using the *Super*-OLAC, which features a high cooling rate and cooling uniformity.

5.2 Steel Products for Architectural Construction

High strength plates are required as steel frame materials for high-rise construction in urban areas. On the other hand, in view of the fracture damage to beam edge welds in the Hyogoken-Nanbu Earthquake (Kobe Earthquake, 1995) there is a heightened need for high performance steel products with a low yield ratio (yield point/tensile strength), high toughness, and good weldability in architectural steel frames. Recently, there has also been a heightened need for steel products with improved toughness in the HAZ in the large heat input welding used in box columns. In response to these needs, JFE Steel developed a steel plate with a lower yield point value of 385 N/mm², "HBL385 (High-Building 385)," as a high strength steel product which offers a combination of economy, seismic resistance, and weldability, making full use of advanced TMCP technology with the *Super*-OLAC, and received material authorization from Japan's Minister of Land, Infrastructure and Transport. In addition, JFE Steel has also developed and commercialized high HAZ toughness steels of tensile strength from 490 N/mm² to 590 N/mm² grade steels for large heat input welding.

5.3 Steel Products for Bridges

Because bridges are important structures in the social infrastructure, high quality and advanced fabrication techniques are required. With larger scale structures and heightened requirements for high efficiency in fabrication in recent years, high performance, high strength steel plates which offer high strength and high toughness in combination with weldability and economy have been strongly demanded. For this need, JFE Steel developed and commercialized an as-rolled SM570TMC steel plate with an optimized balance of strength and toughness by making maximum use of the functions of the *Super*-OLAC and controlling hardenability by micro-addition of alloy elements. This technology was also introduced in an extremely-low carbon banitic-type high strength steel with a carbon content of less than 0.02 mass%, realizing production of products corresponding to the newly-proposed standards BHS500(W) and 700 W[7], aiming at rationalization of design/fabrication and higher performance in bridges. Welding hardening is dramatically reduced, while also achieving high strength, and because the steel is an as-rolled product, it is possible to meet short deadlines.

5.4 Steels for Construction/Industrial Machinery

High strength steels for construction/industrial machinery, represented by JFE-HITEN780LE, were developed exclusively by JFE Steel in order to reduce weight, and are used in various types of parts. Among these, 780 N/mm² grade steel is used in the boom and outriggers (legs which are extended on two sides to fix the car) of rough-terrain cranes (large-scale crane car).

By applying the *Super*-OLAC and HOP, it is possible to secure excellent low temperature toughness in the −40°C low temperature region.

In the field of abrasion resistant steels, where special requirements such as abrasion resistance, bending formability, and impact resistance have become increasingly strict, JFE Steel supplies a new abrasion resistant steel, Everhard 360LE, which has excellent toughness at −40°C simultaneously with high hardness and high ductility. Commercialization of this product was realized by the high speed cooling and uniform cooling capabilities of the *Super*-OLAC.

The two newly-developed steels mentioned above both guarantee C_{eq} (Lloyd's equation) of 0.40 mass% or less, making it possible to reduce the preheating temperature by 25–50°C in comparison with conventional steels.

5.5 High Strength Steels for Pressure Vessels

Various kinds of plates are used in the field of energy, for example, in energy storage facilities, chemical plants, and power plants. In recent years, simultaneously with the adoption of large-scale equipment and more severe operating and service conditions, increasingly strict performance requirements have also been applied to materials to achieve higher welding efficiency with the aim of reducing construction costs. These requirements include improved weldability and higher reliability, such as welds with high strength, welded joint toughness, etc. To meet such requirements, JFE Steel developed a high performance 610 N/mm² grade high strength steel which makes it possible to reduce the preheating temperature and weld hardness by making full use of advanced material design and the innovative manufacturing technologies described above.

New products such as steel plates for use in the side plates of large-scale oil storage tanks, etc., which are constructed by high efficiency, large heat input electro gas welding, 610 N/mm² grade high strength steel plates for large heat input welding, and high toughness 610 N/mm² grade high strength steel plates for low temperature use, which also provide low temperature toughness to approximately −50°C[8], were also achieved by a fusion of material property design employing microalloying elements, preconditioned on use of the *Super*-OLAC, and advanced plate manufacturing technology, and are expected to meet diverse needs in the future.

5.6 Steels for Linepipe

With the development of oil and gas fields in arctic regions and deep sea areas made possible by progress in reducing the cost of oil and gas field drilling technologies and long-distance transportation technologies, there is a trend toward long-distance pipe lines, and the properties of the fluids transported have also become more diverse. Requirements in the linepipes used include high strength, excellent low temperature toughness, and weldability, and furthermore, with fluids containing H_2S, sour service properties (resistance to hydrogen induced cracking and sulfide stress corrosion cracking). Moreover, in linepipes where large deformation is expected, for example, in frozen soil, high deformation performance has also become a requirement.

JFE Steel is continuing to develop linepipes which are capable of satisfying these diverse, strict property requirements by applying the *Super*-OLAC, and is now commercially producing the world's highest strength linepipe, CSA grade 690 (X100 grade equivalent) for the first time in the world by applying the *Super*-OLAC. The *Super*-OLAC has also been applied to the production of high strength linepipes for sour service and a high deformation linepipe, "HIPER," with 1.5 times higher buckling strain than conventional steel pipes.

6. Conclusion

This paper has introduced JFE Steel's revolutionary plate manufacturing processes, the new accelerated cooling technology, *Super*-OLAC, and the on-line heat treatment process, HOP, which uses the world's first and largest induction heating method for plates. These technologies have made it possible to produce high performance plates which satisfy the diverse processing and property requirements of recent years. Unique JFE Steel products made possible by the features this advanced equipment were also described by field of application. JFE Steel is continuing to create "only one" and "number one" products which make full use of this innovative equipment in order to meet stricter and more diverse requirements for new steel plates.

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