Thick Plate Technology for the Last 100 Years: A World Leader in Thermo Mechanical Control Process

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The history of construction of thick plate mills in Japan and trends in the development of rolling technology (gauge control, plan view control, and crown control) during the 100 year history of plate technology in this country are discussed in outline, and the Thermo Mechanical Control Process (TMCP) is reviewed.

In 1901, the blast furnace at the state-owned Yawata Steel Works was blown-in and the medium gauge plate mill was started up, followed by startup of a 3-high rolling mill in 1905. Today, Japan has an annual thick plate production capacity of more than 10 million tons. Various important technical advances have also been achieved over the years, including gauge control, plan view pattern control, and crown control. The Thermo Mechanical Control Process was applied to controlled rolling for the first time in the 1960s, and accelerated cooling was applied in the 1980s. These technologies first reached full maturity in Japan and are now global technologies. The heat-treatment on-line process was also developed and continues to be a world-leading technology.

KEY WORDS: plate; 4hi; gauge control; crown control; plan view control; thermo mechanical control process; control rolling; accelerated cooling; heat treatment on-line process.

1. Introduction

In the spring of 1980, an author at the NKK (now JFE Steel) Fukuyama Works Plate Mill would have noticed that the view of the rolling mill from the hot leveler was completely obscured by clouds of rising steam, even though it was not winter. Looking back 180° toward the cooling bed, he would have seen black steel plates that had been water-cooled after rolling alongside red-hot plates rolled by the conventional process, and just like living creatures, those water-cooled plates gradually changed shape as their temperature decreased, and warps appeared in places. According to operators at the site, this was the situation a few months before the startup of the world’s first On-Line Accelerated Cooling device, or “OLACTM.” Although this new technology was even ridiculed as a “plate warping machine,” after various adjustments and improvements, commercial operation began in August of the same year, and in only a few years, all steel makers in Japan had installed their own accelerated cooling devices. Thus, “OLAC™” raised the curtain on this new technology, which Japan named TMCP, as the abbreviation of “Thermo Mechanism Control Process.” Japan is the world’s leader in TMCP technology, and the fact that TCMP is recognized as a world-class technology is a point of great pride among Japanese plate engineers.

This paper, entitled “Thick Plate Technology for the Last 100 Years,” presents an overview of the history of plate mill construction and the development of rolling control technologies (gauge control, plan view control, and crown control) and reviews the progress in controlled rolling, accelerated cooling, and online heat treatment technology in TMCP, a field to which the author has devoted his entire working life.

In this review, the naming which various companies adopted for rolling methods, accelerated cooling equipment, etc. is used as-is because generalized names cannot adequately distinguish or express the concepts of the developers or the real nature of the technologies.

2. History of Plate Mill Construction

The completion of TOKYO SKYTREE in 2012 is still fresh in memory. That structure, which is the world’s tallest free-standing steel tower, brings together Japan’s best technologies. Virtually the entire SKYTREE consists of steel pipes produced from plate materials. With a maximum thickness of 100 mm and a maximum diameter of 2300 mm, approximately 41,000 tons of steel pipes were used in this remarkable structure.

Figure 1 shows a comparison of the Eiffel Tower and Tokyo Tower from the viewpoint of iron and steel materials. During the period of 123 years between the completion of the Eiffel Tower in 1889 and TOKYO SKYTREE in 2012, steel materials have progressed from wrought iron to mild steel, and later to high-strength steel pipes, and their strength has also increased dramatically. It
is also worth noting that construction methods have evolved from rivets to welded structures in spite of this high strength. The manufacturing technologies for the materials that realized this are the result of progress in steelmaking, refining, and casting technologies and heat treatment and TMCP technologies for plates since the Second World War. The following examines the history of construction of plate mills in Japan based on these developments.

For a detailed description of the history of plate mill construction, the reader may see “History of Plate Technology in Japan,” which was published in February 2001. The present technical history is not a simple time-series exposition of technologies; rather, the actual condition of plate mill construction and the development of rolling technologies and TMCP technologies are organized in the form of a narrative. The author hopes that the reader will feel the passion of the pioneers in this field for construction and development, and this will be a source of encouragement for engineers and researchers as they take on the challenges of the era of mega-competition in the years to come.

In 1901, the blast furnace at the state-owned Yawata Works was blown in and the medium section mill began operation. This was followed by the startup of No. 1 Plate Mill (3-high rolling mill) in 1905. The Japanese iron and steel industry grew rapidly in the second half of the 1930s. In addition to the mills mentioned above, Yawata Works No. 2 Plate Mill was started up, and other new plate mills came on-stream at NKK’s Tsurumi Works, Kawasaki Steel’s Fukui Works, and Amagasaki Iron and Steel’s Amagasaki Works. In 1941, a 4-high rolling mill with the world’s longest roll barrel length of the time, 5,300 mm, was started up at Japan Steel Works, Ltd. to produce extra-thick, wide armor plate for the Japanese Navy’s battleships and aircraft carriers.

Following the Second World War, aging and obsolete plate mills were shut down and replaced by new plants with rolling mills having barrel lengths of 4,700–4,830 mm at Nippon Steel’s Kimitsu and Nagoya Works, NKK’s Fukuyama Works, Kobe Steel’s Kakogawa Works, and Sumitomo Metal’s Kashima Works. These plants are still in operation today. Moreover, due to restrictions on plant space, these plate mills adopted “Japanese original” layouts that considered in-plant logistics, thus shaking off the conventional European and American models.

In 1976–1977, plate mills with roll barrel lengths of 5,500 mm were started up at Kawasaki Steel Mizushima Works, NKK Keihin Works, and Nippon Steel Oita Works. These were state-of-the-art “jumbo” mills featuring linear layouts, automation utilizing computers, and high productivity.

Figure 2 (revision of Ref. 2) shows the transition of plate production volume and plate mill startups and shutdowns in Japan. After the period of stagnation following the war, production recorded a peak of 17.59 million tons in 1974, supported by a shipbuilding boom and demand for linepipe in the former Soviet Union. However, due to the aftereffects of the Oil Crisis of 1973 and other factors, production cuts continued, and over the 10 years from 1977, Nippon Steel’s Hirohata Works Plate Mill, Kawasaki Steel’s Mizushima Works No. 1 and Chiba Plate Mills, and Sumitomo Metal’s Wakayama Works Plate Mill were shut down, and production remained on a level of 10 million tons or less. At the beginning of the 21st century, plate production enjoyed a renewed era of prosperity, buoyed by the economic development of China. Japan’s plate mills are still the world’s leading facilities. Recently, however, the startup of new state-of-the-art plants in Korea and China and the recession in shipbuilding following the Lehman Shock have forced Japanese makers to refocus production from quantity to quality, as can be understood from the shutdown of the plate mill at Nakayama Steel Works in 2012.

<table>
<thead>
<tr>
<th>Eiffel Tower</th>
<th>Tokyo Tower</th>
<th>TOMYO SKY TREE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>1889</td>
<td>1958</td>
</tr>
<tr>
<td>Material Yield Strength</td>
<td>~200MPa</td>
<td>Mild Steel (Angles) &gt;325MPa</td>
</tr>
<tr>
<td>Weight</td>
<td>73000ton</td>
<td>42000ton</td>
</tr>
<tr>
<td>Joining</td>
<td>Rivet</td>
<td>Rivet</td>
</tr>
</tbody>
</table>

Fig. 1. Comparison of towers.13

Fig. 2. History of plate mill production.
3. Progress of Rolling Technology

3.1. Gauge Control and Plan View Control

Figure 3 shows the history of the key technologies in rolling control. Supported by the introduction of process computers, reduction pattern control was established in the first half of the 1970s. Next, various types of models based on rolling theory and multiple regression of sensor data were developed and learning control was established. In the second half of the 1970s, the changeover from electric screw Automatic Gauge Control (AGC) to high response oil hydraulic AGC progressed, and plate thickness deviations due to in-bar load fluctuations were remarkably reduced by applying lock-on AGC, which actively utilized the response of hydraulic technology. Absolute AGC, which is based on a high accuracy gauge meter model utilizing the computer, was also introduced, and deviation relative to the target plate thickness was improved. Since the second half of the 1980s, proximate γ-ray gauge meters have been installed near the finishing mill, and advanced plate rolling control systems like that shown in Fig. 4 have been established by minimizing the effects of model error by use of monitor AGC, feed-forward AGC, and model learning utilizing this γ-ray gauge meter. LP (Longitudinally Profiled) steel plates, in which the plate thickness is changed continuously in the longitudinal direction, were also developed by applying this plate gauge control technology. Direct-drive AGC, in which the hydraulic power unit is installed in close proximity to the AGC device, also contributed to improved response. An example of the change of thickness accuracy as a result of the development of these technologies is shown in Fig. 5.

As one noteworthy development in plan view control, around 1980, the rolling methods called MAS rolling

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<tbody>
<tr>
<td>1. Control Model</td>
<td>Digitalization &amp; Standardization (gauge &amp; section)</td>
<td>Rolling Load, Temperature, Pre-deformation, Resistance &amp; Gauge Meter Model</td>
<td>Crown &amp; Finishing Control Model</td>
<td>Plan View Pattern Control Model</td>
<td>Edging Model</td>
</tr>
<tr>
<td>2. Control Actuator</td>
<td>Electric AGC</td>
<td>Hydraulic AGC</td>
<td>Edge Close to Mill</td>
<td>High Power Rail Mill</td>
<td>Variable Speed AC Motor</td>
</tr>
<tr>
<td>4. Process Computer</td>
<td></td>
<td>DDA (I)</td>
<td>16-bit 0.9MIPS Data Way</td>
<td>32-bit 2.7MIPS Optical Data Way</td>
<td>32-bit 4.8MIPS High Capacity &amp; High Speed Data Way</td>
</tr>
</tbody>
</table>

Fig. 3. History of rolling control technology. © 2015 ISIJ
(Mizushima Automatic plan view pattern System rolling)\(^9\) and DBR (Dog Bone Rolling)\(^10\) were developed and applied in commercial operation, enabling rolling of rectangular plates. In simple rolling, the top and tail ends and side edges take a drum (convex) shape or barrel (spool) shape, depending on the reduction ratio and broadside rolling ratio. In contrast, with these rolling methods, the thickness of the head and tail ends is increased by taper rolling in the final pass after sizing rolling and broadside rolling, and a rectangular shape is obtained by turning the plate 90° before the next rolling pass, as shown in Fig. 6. These technologies were realized by predicting unsatisfactory shape by a plan view prediction model and applying the appropriate thickness difference based on the law of constant volume. The accuracy of these technologies was further enhanced by the introduction of the slab profile meter and edger and use in combination with Automatic Width Control (AWC).

3.2. Crown Control

Among high dimensional accuracy rolling control technologies, Work Roll Shift (powerful work roll binder and long-shift),\(^11\) Continuously Variable Crown (short roll shift), and the Pair Cross mill\(^12\) were introduced as actuators of shape control mills (Fig. 7). The bender is a method which controls plate crown by applying bending force to the two end parts of the roll, while also compensating for roll deflection. However, because plates are wider than hot-rolled sheets, there are limits to control of plates using only the binder. In work roll shift, the top and bottom work rolls are shifted in opposite directions in each rolling pass, thereby changing the region of contact between the work rolls and backup rolls, in order to compensate for deflection of the work rolls. As a strong point of this technique, application of work roll shift in combination with the above-mentioned bender realizes a wide crown control range, as shown in Fig. 8.\(^11\) Roll shift reaching as much as 1 m has the effect of dispersing roll wear and also makes an important contribution to schedule-free rolling, as there are no restrictions on the rolling width schedule.\(^11\) In short roll shift mills, the crown control function is enhanced by using a work roll profile with a cubic curve or trigonometric curve. In the pair cross method, the amount of equivalent crown is controlled by crossing the top and bottom work rolls and their backup rolls in pairs relative to the rolling direction; this method has the advantage of high control capacity independent of rolling width (Fig. 9\(^12\)).

3.3. Changeover to AC Motors and Powerful Leveler

Looking at rolling technology in the 1990s, the main direction in practical application of the aforementioned technologies was manufacturing based on improvement of the levels of various models. In addition, the changeover to AC mill motors was an important hardware-related item. The advantages of the changeover from DC to AC motors included (1) Improvement of control response by digital control (Fig. 10\(^13\)), (2) Reduction of the number of rolling passes as a result of increased mill capacity (improved efficiency

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**Fig. 6.** MAS rolling method.\(^9\)

**Fig. 7.** Schematic illustration of representative crown control mill.

**Fig. 8.** Control range of crown obtained by calculation.\(^10\)

**Fig. 9.** Comparison of plate crown between pair cross and conventional mill.\(^13\)
by ① and ②), and ③ Improvement of maintainability due to the use of commutator-free motors.

Although not a rolling technology, in 1999, a powerful 5 000 ton class cold leveler was applied in commercial operation\textsuperscript{14}) as a means of mechanically controlling the flatness problems and residual stress caused by rolling and accelerated cooling. Use of this technology has now expanded to all mills in Japan. This type of powerful bender does not simply perform leveling (straightening) by applying a high load, but also makes it possible to control residual stress uniformly in the plate transverse direction by arranging multiple hydraulic cylinders or wedges to enable correction of deflection in the rolls and housing during leveling (Fig. 11\textsuperscript{14}). It is particularly effective for suppressing deformation after longitudinal cutting of plates and slit-slot cutting of shipbuilding steels.

It may be noted that the 4 500–5 000 mm rolling mill with bender plus short roll shift rolling mill, edger, and deflection-corrected leveler have become standard equipment in virtually all new plate mills constructed in Korea and China since 2000. As the proximate γ-ray thickness gauge is also installed as an option, their latent capacity is high, and they are expected to demonstrate those functions in the future. In the face of this intense competition, Japanese mills must also promote further development.

4. Progress in TMCP Technology

4.1. Metallurgy of TMCP

The microstructure of steel changes depending on the chemical composition of the material, deformation, and the heat cycle in heating and cooling, and mechanical properties also change depending on the microstructure. In plate manufacturing, microstructure control such as grain refinement, etc. and texture control are also possible by applying deformation in the rolling process and online accelerated cooling and heating. These techniques play an important role in improving the safety of structures by realizing high strength, high toughness, and high weldability. What makes this microstructural control possible in an online process is the thermo mechanical control process (TMCP), in which controlled rolling and accelerated cooling are combined online. TMCP has been the subject of many reviews; however, for a detailed explanation of its history and use in microstructure/material property control, the reader may see “Controlled Rolling and Controlled Cooling”\textsuperscript{15}) by Isao Kozasu.

Figure 12 shows an example of the layout of online cooling and heating facilities. Figure 13 shows the relationship of these various processes and the microstructure/strengthening mechanism. (revision of Ref. 16)). Figure 14\textsuperscript{17}) shows a comparison of the microstructural changes in conventional rolling, controlled rolling, and accelerated cooling. In controlled rolling, low temperature heating is performed in the slab heating stage to suppress the grain growth of the austenite single phase. Because the first half of rolling is per-
formed in the recrystallization temperature region, equiaxed grain refinement is promoted by recrystallization. In the second half of rolling, grain elongation is promoted because rolling is performed in non-recrystallization region, deformation bands which form nucleation sites for subsequent transformation are introduced in the grains, and ferrite grains are refined.\textsuperscript{18–20} If accelerated cooling is combined with this controlled rolling process, austenite can be supercooled, and this adds a mechanism for further grain refinement by the ferrite low temperature transformation effect (increase of transformation nuclei and suppression of grain growth) and transition from pearlite to the bainite transformation by the quenching effect. When the steel composition includes precipitation-hardening elements such as Nb, Ti, V, etc., precipitation occurs during air cooling after interruption of water cooling; this also contributes to precipitation hardening, and as a result, it is possible to secure strength without heavy addition of alloying elements. Thus, accelerated cooling is an essential process when improved weldability is required. In particular, Nb is an extremely useful element in this TMCP, as it has the functions of suppressing grain growth during slab heating, increasing the recrystallization/non-recrystallization transition temperature, improving hardenability, and precipitation hardening.\textsuperscript{21}

### 4.2. Controlled Rolling Process

Controlled rolling has a long history. In the initial stage, it appears to have been used in Europe in the 1900 decade. Its popularization and development in Japan date from the 1960s, and were the result of large orders for high strength linepipe with excellent low temperature toughness for use in cold regions, beginning with the Trans-Alaska Pipeline System. The specifications of these products were extremely severe at the time, namely, a plate thickness of around 0.5 inches, outer diameter of 48 inches, API standard X60-X65, and impact value of 50 ft-lbs at a Charpy test temperature.
of \(-10^\circ\text{C}\). Since this was a major project requiring 500,000 tons of steel materials, research and development were carried out in competition by all Japanese steel makers, and composition design was performed using a small amount of Nb. Based on the development results, a Special Issue on “Research and Development of Non-heat Treated High Tensile Strength Steel” was published in *Tetsu-to-Hagané* in 1972.22) As an extension of this technology, the “SHT (Sumitomo High Toughness) Process” 23) was proposed in the latter 1970s. SHT actively utilized transformation in order to realize grain refinement by performing heating and rolling twice each in an online process. However, because this ran counter to the trends toward energy-saving and process-saving, that approach has now been replaced by controlled cooling. Controlled rolling in the two-phase region,24,25) which is not limited to the austenite region but was extended to the dual-phase region of austenite plus ferrite, has the problems of low efficiency and high rolling load, but is nevertheless an effective rolling process for meeting drop-weight tear test requirements for brittle fracture of linepipes.

Controlled rolling not only refines the microstructure, but also achieves texture in the steel product, and this is a cause of mechanical properties and acoustic anisotropy.26) In recent years, with the construction of high power plate mills and modernization from DC to AC mill motors, the microstructure control region has expanded, including microstructure plus texture by low temperature, heavy reduction rolling. A process called “Super-CR,” in which cooling equipment is installed in the side guides in close proximity to the rolling mill, has also been developed and applied practically in order to shorten the waiting time for plate temperature adjustment, which had been a drawback for the process in controlled rolling.27) This new process can also be applied to control of material quality, and unprecedented control of material properties by 2-stage cooling is also possible when it is used in combination with existing accelerated cooling.

### 4.3. Accelerated Cooling Process

Accelerated cooling is a material property control technology in which the strength, toughness, and weldability of steel products are increased in an online process. Initially, study focused on direct quenching by water cooling to room temperature after rolling, but then shifted to the accelerated cooling process, in which water cooling is interrupted before reaching room temperature, aiming at self-tempering of the steel. As this accelerated cooling process in combination with controlled rolling makes it possible to increase strength without sacrificing toughness,28) it first flowered in Japan during the 1980s and has now become a global technology. Today, it has gained acceptance throughout the world as standard equipment for production of high-grade steel plates while also enabling direct quenching. The reason for its flowering in Japan was due to a fusion of progress in equipment technology accompanying the startup of plate mills during Japan’s high economic growth era, as described in Chapter 2, and technology for building material properties into products by practical application of controlled rolling. It is also noteworthy that Japan has continued to lead the world in this area of technology.

Accelerated cooling of steel materials suppresses grain growth and has a quenching effect.29–31) This means it is possible to obtain various microstructures and strengths while simultaneously reducing the use of alloying elements.

| Table 1 | Shows the specifications of representative accelerated cooling facilities.32–35) Initially, the installation position was divided into two types, *i.e.*, either before or after the hot leveler, depending on restrictions related to other equipment and differences in the basic concept. The main stream was arrangement before the leveler, as this offered a high degree of freedom in the cooling start temperature and easy control of material properties. Recently, however, an increasing number of pre-levelers have been constructed before the accelerated cooling equipment, based on the recognition that is important to secure the flatness of plates before water cooling from the viewpoint of strain. Here, the
key points for accelerated cooling equipment are considered to be (1) Uniform cooling of the entire plate, (2) Precise control of the water-cooling start and stop temperatures, and (3) Control of the water-cooling rate. Particularly where uniform cooling is concerned, control naturally becomes difficult with materials like thick plates that have a wide width and large thickness. First, in securing uniformity in the plate transverse direction, the drainability of the top side is an issue (this is not a problem on the bottom side). Since the water that accumulates on the top side mainly runs off to the sides, overcooling of the side edges in comparison with the central part is a problem. Because the temperature difference between the transverse center and the edges becomes excessive, particularly in the case of low cooling rates, ingenuity is necessary, as seen for example in edge masking, transverse direction water flow rate control, and similar techniques, and it is also important to improve the related control models. The next problem is asymmetry of cooling on the top and bottom sides. Due to gravity, cooling will not be symmetrical on the top and bottom sides if the same method, same nozzle, and same flow rate are used. Various measures have been taken to solve this problem, including adoption of different nozzle types in top and bottom side, changing the top and bottom flow rates or distances from the plate, and the like. More than a quarter-century has passed since the first generation of accelerated cooling technology using these various methods, and during this period, modernization and revamping have been carried in pursuit of uniform cooling.

The “Super-OLAC™,” which appeared in 1998, is the second generation accelerated cooling technology which aims at nucleate boiling over the entire plate surface. In water cooling of steel materials, the heat transfer phenomena and boiling phenomena are (1) Nucleate boiling, in which the cooling water is in direct contact with the steel and heat is transmitted by formation of air bubbles, and (2) Film boiling, in which a film of water vapor forms between the steel and cooling water, and heat is transmitted through this vapor film. It goes without saying that the cooling capacity of nucleate boiling is higher. In conventional cooling methods, changing the top and bottom flow rates or distances from the plate, and the like. More than a quarter-century has passed since the first generation of accelerated cooling technology using these various methods, and during this period, modernization and revamping have been carried in pursuit of uniform cooling.

Table 1. Specification of ACC facilities,31–34)

<table>
<thead>
<tr>
<th>Country</th>
<th>Company/ Mill</th>
<th>Start up</th>
<th>Name of system</th>
<th>Location (before, after or between H.L..*)</th>
<th>Type of ACC equipment</th>
<th>Nozzle</th>
<th>DQ availability</th>
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<tbody>
<tr>
<td>Japan</td>
<td>A</td>
<td>1984</td>
<td>CLC</td>
<td>just after</td>
<td>1st part: Slit jet</td>
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<td>○</td>
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<tr>
<td></td>
<td>B</td>
<td>2005</td>
<td>CLC-µ</td>
<td>just after</td>
<td>2nd part: Spray</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>1986</td>
<td>CLC</td>
<td>just after</td>
<td>1st part: Slit jet</td>
<td>○</td>
<td>○</td>
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<tr>
<td></td>
<td>B</td>
<td>1983</td>
<td>DAC I</td>
<td>before</td>
<td>2nd part: Spray</td>
<td>○</td>
<td>○</td>
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<tr>
<td></td>
<td>C</td>
<td>1985</td>
<td>KCL(DBQ)</td>
<td>between</td>
<td>Laminar</td>
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<td></td>
<td>A</td>
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<td>DAC II</td>
<td>before</td>
<td>Mist</td>
<td>○</td>
<td>○</td>
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<td></td>
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<td>DAC-n</td>
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<td>Corridor flow</td>
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<td>A</td>
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<td>before</td>
<td>Corridor flow</td>
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<td>○</td>
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<tr>
<td></td>
<td>B</td>
<td>1983</td>
<td>MACS(DQ)</td>
<td>before</td>
<td>Immersion+Stir</td>
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<td>before</td>
<td>Corridor flow</td>
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<td>○</td>
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<td></td>
<td>A</td>
<td>1989</td>
<td>ADCO</td>
<td>before</td>
<td>Mist</td>
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<td>○</td>
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<tr>
<td></td>
<td>B</td>
<td>1986</td>
<td>MULPIC</td>
<td>before</td>
<td>Pipe</td>
<td>○</td>
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<td>A</td>
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<td>MULPIC</td>
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<td>MACOS</td>
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<td>J</td>
<td>1995</td>
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<td>Mist</td>
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<td>between</td>
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<td></td>
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<tr>
<td></td>
<td>N</td>
<td>2001</td>
<td>ADCO</td>
<td>before</td>
<td>Mist</td>
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<td>○</td>
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*H.L..Hot leveler(s)
plate expand because the cooling capacity is higher in low temperature parts (nucleate boiling) than in high temperature parts (film boiling) (Fig. 15). In conventional cooling, non-uniform cooling caused problems, especially on the top side of plates, because nucleate boiling occurred directly under the nozzles due to the effect of stagnant water, but film boiling occurred in the surrounding area. By applying ingenuity to the water flow rate and water flow, the “Super-OLAC™” makes it possible to perform cooling in the nucleate boiling condition over the entire plate surface on both the top and bottom sides, and realizes uniform cooling and a high cooling rate equivalent to the theoretical limit (Fig. 16). Figure 17 shows a comparison of the original “OLAC™” which was put into operation in 1980 and the “Super-OLAC™” which is now in operation. Clouds of

Fig. 15. Nucleate boiling - film boiling transition behavior.

Fig. 16. Cooling rate of Super-OLAC™.

Fig. 17. Cooling operation state of a) OLAC™ and b) Super-OLAC™.

Fig. 18. Outview of a) CLD-μ, b) KCL and c) DAC-n.
steam can be seen rising from the “OLAC™,” but in contrast, absolutely no steam can be seen with “Super-OLAC™,” even though the plate is red-hot at the entry side and has been cooled to a gray color at the exit side. From this, it can be understood that “Super-OLAC™” has achieved full-surface nucleate boiling, as described above. Even though “Super-OLAC™” is also an accelerated cooling device, remarkable progress was achieved in a period approximately 20 years. This kind of tireless research and development is the driving force for Japan’s competitiveness in plate technology.

Figure 18 shows photographs of other types of accelerated cooling devices.32,33) Recently, plant improvements have been carried out with the aim of covering the range from intensive cooling to mild cooling. In “CLC-μ,” a nozzle that enables uniform cooling even at low flow rates was developed, and selection of a wide range of cooling rates is realized by controlling the flow rate.42) “KCL” features a long cooling zone that also enables simultaneous cooling of the entire plate. This device is equipped with four different types of nozzles, and the flow rate of each type is fixed; cooling at the desired cooling rate is possible by changing the combination of these different nozzles.43) “DAC-n” was revamped to improve cooling stop accuracy.44) As these examples show, Japanese mills have worked to lead the world in 2nd generation accelerated cooling technology based on different concepts and methods, which are also capable of direct quenching. Korea introduced “MULPIC” in 2003 and 2010, and appears to have improved its cooling capacity and realized a higher level in the control model. However, because this is strategic equipment, Korea has not published the details. Including China, attention is focused on the struggle for leadership in online high-grade steel manufacturing backed by new equipment.

4.4. Online Heat Treatment Processes

If online heating is applied in the controlled rolling-accelerated cooling process, an even wider range of microstructure control is possible. The SUF steel manufacturing process may be mentioned as an example. In this process, accelerated cooling is performed during rolling, and a fine microstructure with an average grain size of 2 μm or less is formed only in the surface layer (Fig. 19).46) This process utilizes a phenomenon in which only the surface and subsurface layers are transformed by water cooling, and the ferrite microstructure of those layers undergoes ultra-refinement as a result of recrystallization under rolling at constant temperature when rolling reduction is applied during self-restoration of heat. SUF steel has excellent brittle crack propagation arrest performance because shear lips are formed accompanying plastic deformation, and has a record of use as a steel for shipbuilding.45)

Another example is HOP™ (Heat treatment On-line Process)46) for online heat treatment after accelerated cooling, which was put into practical use at the beginning of the 2000s and represents a further development of high performance steel manufacturing by accelerated cooling equipment. In this method, an electromagnetic coil is used to produce an induction current in the steel plate, and the plate is heated by the heat generated by that current. Among its features, HOP™ is a completely online heat treatment process synchronized with rolling, which makes it possible to meet extremely tight delivery schedules and supports mass production, and when used in combination with accelerated cooling it also further expands the possibilities of new microstructure control by free control of phase transformation and precipitation. Although heating is applied by HOP™ after general controlled rolling-accelerated cooling, a key feature is the fact that heating can be started from any arbitrary temperature, as shown in Fig. 13(k), which had not been possible with conventional off-line heating.

Examples of the use of this technology include low yield ratio (YR) high strength plates for earthquake-resistant building use47) and high strength high deformability linepipe.48,49) Although dual-phase structure control of a microstructure comprising a soft phase and a hard phase is effective for realizing low YR, it is difficult to achieve low YR in high-strength steels due to the difficulty of using ferrite as the soft phase. The process using HOP™ makes it possible to produce a steel in which the soft phase of the matrix is comparatively hard bainitic ferrite, and the hard second phase is a harder island-like martensite, M-A (Martensite-Austenite Constituents). The concept of microstructure control in the series of manufacturing processes by controlled rolling, accelerated cooling, and heat treatment is shown schematically in Fig. 20.48) Accelerated cooling is stopped in the bainite transformation temperature region. Next, in the online heating process below the Ac1 transformation, super-

![Microstructure of SUF steel](image)

Fig. 19. Microstructure of SUF steel.45)
saturated carbon is enriched in untransformed austenite. As a result of this, untransformed austenite which is amply enriched with carbon is transformed to fine M-A in the cooling process. Finally, a complex phase structure in which M-A is randomly dispersed in granular bainitic ferrite is obtained by this process. In obtaining the high strength, low YR microstructure described above, it is essential to stop cooling in the bainite region where untransformed austenite exists, and this can only be realized by online heat treatment. Here, it may be noted that M-A is generally considered to be a harmful microstructure that reduces toughness because it is hard and brittle, but if its fraction, shape, and size can be controlled, and the characteristics of the M-A/matrix interface as such can be modified, deterioration of toughness by M-A can be substantially suppressed.

Due to space limitations, it is necessary to omit a detailed discussion of direct quenching and securing of the welding heat affected zone (HAZ) toughness, which are key technologies in TMCP. For details, the reader may see the series of Nishiyama Memorial Seminars listed in the references.

Figure 21 (revision of Ref. 58) shows the history of development of online accelerated cooling and heat treatment equipment. In the future, development of new TMCP for control of material properties by freely combining this type of cooling and heating, as well as working by rolling, is expected. The keywords will be uniformity of the full length, full width, and top and bottom sides and integrated online treatment. Together with a deepening of metallurgy, it is hoped that Japan will continue to propose these innovative technologies.

6. Conclusion

Finally, the following is a history of awards of the Okochi Prize for achievements in connection with steel plate technology.

- 1976 Establishment of automatic operation technology in plate production
- 1978 Development of manufacturing technology for high toughness, low temperature service steel by special TMCP
- 1979 Development of new plan view pattern control method (MAS rolling method) in plate rolling
- 1981 Development of on-line accelerated cooling method (OLAC) in high-grade thick steel plate production
- 1987 Development of manufacturing technique for clad steel plates by enshrouded casting and rolling process
- 1991 Development of manufacturing technology for heavy thickness high tensile strength steel for building structural use with excellent seismic performance
- 1993 Development of manufacturing technology for high performance “Rolled Clad Plate” using sandwich-type assembled slab
- 2002 Development of on-line accelerated cooling technology by critical cooling rate and its practical application and commercialization in heavy steel plates, shape steel, and hot-rolled steel strip
- 2007 Development of high strength steel plates for large-scale container ships and new ship hull structural design
- 2011 Ultra-low spatter positive polarity CO₂ arc welding technology

Thus, while there have been many changes in products, and more recently, in use technologies, due to automation, rolling technology, TMCP, accelerated cooling equipment, clad steel manufacturing technology, and heat treatment, there is no question that technical development related to thick plates has continued without interruption. In closing, I would like to express my respect for the struggles and achievements of those who went before us, and my expectations for the efforts and progress of the next generation.
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