UDC 621 . 771 : 621 . 783 : 621 . 892

*Technical Review*

# Progress and Prospect of Rolling Technology

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## 1. Introduction

The last three decades were a period of development and commercial application of new rolling processes unique to Japan. These developments occurred in response to shifts in the business environment, such as the energy crisis and changes in steel-consuming industries, while the Japanese steel industry faced with stagnation of production growth. In other words, these three decades covered a period in which the rolling technology of the country was brought to a world- leading position through difficulties. Lately, however, rolling facilities incorporating the latest technology are being commissioned one after another in developing and other countries, and thus, the technical advantage of Japan is dwindling, at least in terms of the equipage of rolling facilities. Given this situation, the following pages present an overview of the rolling technologies Nippon Steel Corporation developed and actually used during these three decades, and describes the prospects for technological advances in steel rolling in the near future.

## 2. Development of New Rolling Processes

### 2.1 Direct linking of cold strip rolling processes

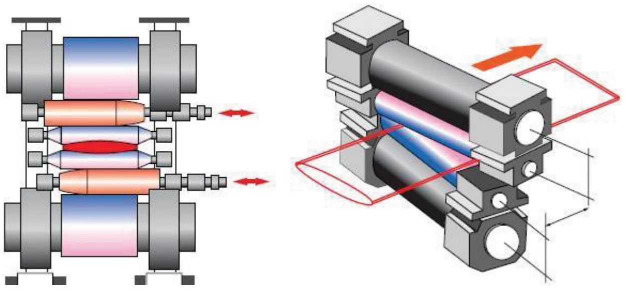
Direct connection of continuous casting and hot rolling for energy conservation was nearly an established practice in 1981 [1], while a significant change was taking place in the field of cold strip rolling. That year, a new process directly linking a tandem cold mill with a pickling line, called a continuous descaling cold rolling mill (CDCM) [2], began commercial operations at the Kimitsu Works. The development of helical turners that enabled direct linking of the two lines running at right angles to each other was instrumental in realizing the CDCM. Then in 1986, a fully-integrated cold rolling and processing line (FIPL) [3] became operational at the Hirohata Works, in which the pickling, cold rolling and continuous annealing processes were integrated in one continuous line, realizing the ultimate form of continuous processing for cold strip rolling.

### 2.2 Development of endless hot strip rolling

When rolling steel sheets on hot strip mills, to avoid a temperature drop in the rolled material, it is necessary to pass it through finishing mill stands at high speeds, which makes the rolling of the head and tail ends of a strip more difficult than on tandem cold mills. For this reason, application of fully continuous rolling, which had long been daily practice in cold rolling, to hot rolling was anticipated. Nippon Steel's Oita Works thus developed a method in which the head end of a rolled material was joined to the tail end of the preceding one by laser welding before entering the finishing mill train in order to make the rolling operation go on without interruption, and applied this method, named endless hot strip rolling, to commercial production [4]. Mill pacing, a technique to accurately control the rolling time of a rolled material and that of the following one, was improved to make the endless hot strip rolling practical by minimizing the idle time. The improvements also resulted in enhancement of the mill productivity when applied to conventional rolling of individual strips.

### 2.3 Crown and shape control during rolling

Needless to say, the most important role of a rolling mill for flat products is to continuously apply plastic working to steel in order to deform it into a sheet of a prescribed thickness. The screw-down device of the mill ensures the longitudinal homogeneity of the product thickness, but to control the thickness distribution in the width direction, a different actuator is required exclusively for this purpose. As the front runner of the steel industry, Nippon Steel developed, through joint efforts with mill builders, new types of rolling mills equipped with such actuators; typical examples of these mills are the 6-high mill with lateral shifting of intermediate rolls (called the HC mill) [5] and the pair-crossed roll (PC) mill [6], which are shown in **Fig. 1** (a) and (b), respectively.



**(a) HC-mill** **(b) PC-mill**

**Fig. 1 Typical crown control mills**

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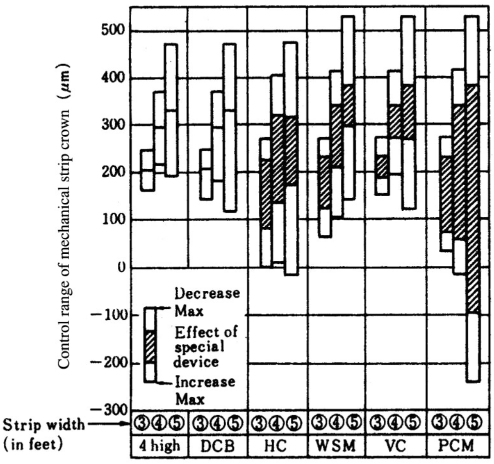


Fig. 2 Crown control capacity for various crown cortrol mills

**Fig. 2** compares, in terms of crown control capacity, various types of rolling mills for flat products that were developed at that time7). One can see in the figure that, while the PC mill has the strongest crown control capacity in all of the width ranges, the HC mill is effective for narrow strips, particularly due to the quick response of the roll benders. Initially, the HC mill was applied to the cold rolling mills, and then to the finishing mill stands of the continuous hot rolling mill of the Yawata Works, which was commissioned in 1982. The PC mill was first used commercially for the continuous hot rolling mill of Hirohata, which was commissioned in 1984, and then for the former stands of the finishing mill train of the continuous hot rolling mill of Nagoya, and also for the finishing stand of the Kimitsu plate mill.

### 2.4 New rolling processes for long products

#### (1) H-shapes with uniform beam depth, "NITTETSUHYPER BEAM®"

Nippon Steel began commercial production of rolled H-shapes for the first time in Japan in 1959 and, ever since, has developed technologies to meet the widely varied requirements of users of the product, which is offered in a large number of size series. What deserves special mention is the production of H-shapes with uniform depth and width using the NITTETSUHYPER BEAM ® method, which was commercialized in 1989 (see **Fig. 3**). This product was meant to replace welded H-shapes; the web height and the flange width of a size series are constant regardless of the flange and web thickness. As seen in **Fig. 4**, the method consists of expanding the distance between the flange inner faces using a rolling mill with skewed rolls8), and finishing of the rolling through a universal mill with variable-barrel width horizontal rolls9). An additional method was developed whereby uniform flange width is obtained through edger rolling using variable-caliber depth edger rolls10), and yet another for controlling residual stress by water cooling the flanges during and after rolling11). As a result, NITTETSUHYPER BEAMs of 177 different sizes in 26 size series up to 900×300 mm with high dimensional accuracy were made available.

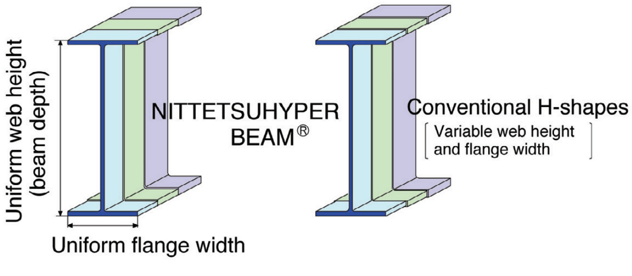


Fig. 3 H-shapes with uniform beam depth: NITTETSUHYPER BEAM®

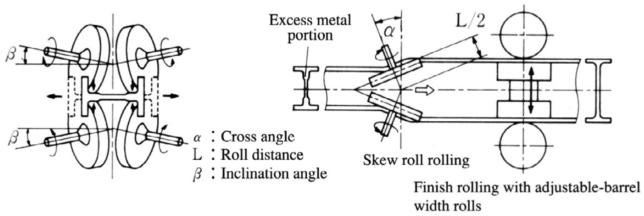


Fig. 4 Technologies for controlling beam depth uniformly

Thereafter, using FEM analysis based on NSCARM12) (to be explained later), an efficient roughing rolling method for large sectional areas was developed, and thanks to this method, the size variety of the NITTETSUHYPER BEAM ® was further expanded to 592 sizes in 47 size series up to 1,000 × 400 mm.

#### (2) Hat-section sheet pilings

Nippon Steel's technical development for sheet pilings has focused on structural reliability, ease of driving, and economical efficiency. The activities yielded three size series of U-section sheet pilings with a 600 mm effective width that were launched to the market in 1997, and two size series of hat-section sheet pilings that were introduced in 2005. These new series of hat-section pilings are characterized by the following: an effective width of 900 mm, the largest in the world; non-symmetric joints at the ends to enable driving without having to overturn every other piece; high structural reliability because the joints are at the outer face of the wall and consequently no slipping of the joints between adjacent pieces to decrease wall stiffness; and high economical efficiency due to reduced thickness. A new rolling method was developed and applied to commercial production of this product, which consisted of (1) bending for formation of the joints (see **Fig. 5**)13), in which the bottoms of the elbow-shaped joints of the material are bent after intermediate rolling by vertically pressing between the roll grooves for finishing rolling, and (2) one-groove, multi-pass rolling (see **Fig. 6**)14), in which products virtually free from dimensional or shape defects around the joints are obtained by slanting the joint bottoms during intermediate rolling in order to homogenize

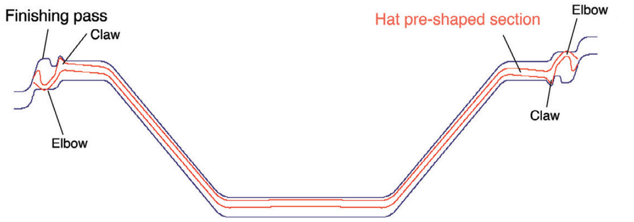


Fig. 5 Newly developed interlock forming method during finishing pass

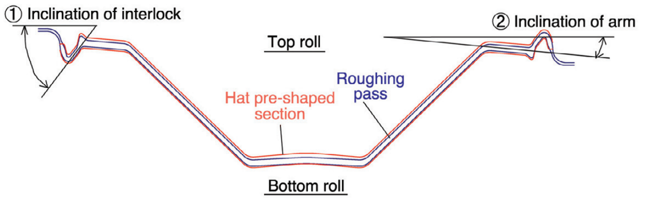


**Fig. 6 Roughing pass method of hat pre-shaped section with asymmetrical interlocks on both sides**

the elongation distribution in the width direction, and by slanting the joint arms such that the principal axis of inertia of the rolled section runs in right angles to the roll axes.

## 3. Computer Control of Rolling Processes

Of the fields of technology related to steel rolling, it was in the field of computers that the most remarkable innovations were achieved over the last 30 years. The use of computers for the control of rolling processes advanced dramatically, especially in the rolling of flat products.

### 3.1 Gauge control

Gauge control is one of the fundamentals of sheet/plate rolling. Conventionally, there were two methods of automatic gauge control (AGC): gauge-meter AGC and monitor AGC. Using gauge-meter AGC changes in the rolling load are detected, and screw-down is controlled accordingly, while compensating for equipment deformation due to mill stretch. In contrast, with monitor AGC, the sheet thickness is measured with a thickness measurement system at the delivery side of the mill stand, and the reading is fed back for screw-down control. Although these two methods were used for a long period, the former had a problem in accuracy and the latter in response time.

To solve these problems, on the basis of the mill deformation calculation model for crown control (to be explained in the following Sub-section 3.2), Nippon Steel developed a high-accuracy calculation model for mill stretch[15)], and this model was applied to actual rolling in the form of absolute gauge-meter AGC. With this technology, it became possible to estimate sheet thickness accurately from moment to moment based on the measured rolling load, which led to a remarkable improvement in thickness accuracy, especially at the head end of the strips, as shown in **Fig. 7**[16)].

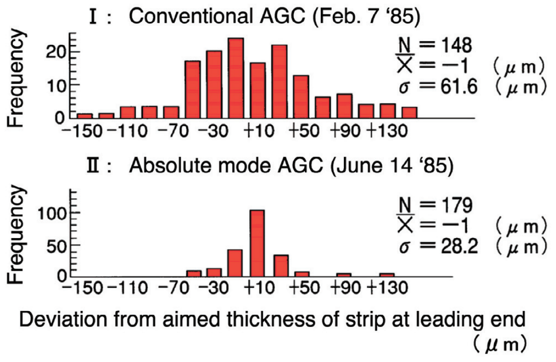


**Fig. 7 Improvement of gauge accuracy through application of absolute mode AGC**

### 3.2 Crown control

For commercial use of the HC and PC mills, Nippon Steel focused its efforts on developing on-line calculation models in order to enable full utilization of their new functions. It was essential that the models were suitable for high-speed calculation and were so structured as to be able to quickly obtain the setting references for the actuators from the target crown and shape. Before Nippon Steel dug into the issue in depth, the setting references had been calculated mostly using regression equations derived from tests or calculations using off-line models. However, the accuracy and applicability of such methods were naturally limited, and it was difficult to ensure high reliability in every possible rolling condition.

Given these limitations, Nippon Steel adopted a basic development policy to work out equations for the theoretical calculation of the sheet crown as far as was possible. As a result, it became clear that a set of such basic equations could be formulated that expressed the sheet crown at the delivery side of a mill using the linear combination of the mechanical strip crown, which is defined by the conditions of the mill, and the crown at the entry, as well as the coefficient of the linear combination using a crown ratio heredity coefficient. In addition, a system of sheet crown models was developed by composing mechanical strip crown calculation equations from theoretical formulae using the superposition of roll deformations under different conditions[17)]. This system made it possible, on the hot strip mill of Yawata, to control the sheet crown in a manner free from restrictions (**Fig. 8**) for the first time in the world[18)]. Thereafter, the developed system was applied to the company's other hot strip mills.

### 3.3 Intelligent rolling

While the HC and PC mills freed crown control from various restrictions, as explained above, shape (or flatness) control requires mathematical models with degrees of accuracy higher by one order of magnitude or more. For this reason, such control still depends mostly on the skill of the mill operators. To improve the situation, Nippon Steel has developed a totally new mill system called the NSC Intelligent Mill (NIM) that is capable of estimating in real time the distribution of the rolling load in the width direction, which is closely related to the flatness of the rolled sheet, and controlling the load distribution as required. The mill has divided back-up rolls (BURs), each equipped with a load cell and a position control mechanism, that support one of the work rolls, as seen in **Fig. 9**. The NIM system, including the mill control software, was worked out through refinement of the mill analysis technology that the company had accumulated. The NIM system has been commercially applied to a leveler for heavy plates, making use of the powerful shape-correction capacity under extremely light reductions in thickness[19)].

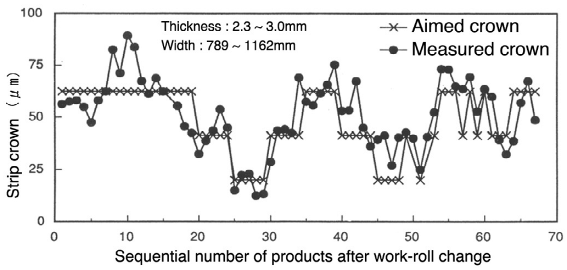


**Fig. 8 Result of automatic crown set-up control**

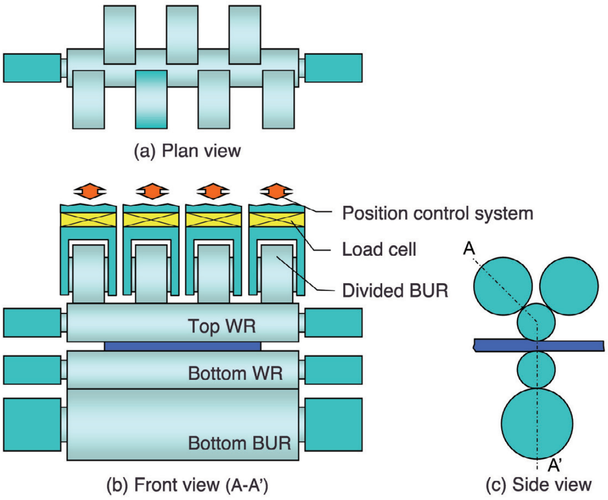


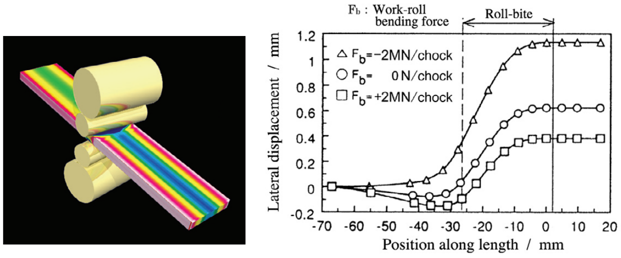
**Fig. 9 Structure of NSC intelligent mill**

**NSCARM** except 2D codes

- ☐ Mandrel rolling
  - ☐ Specialized pre-processor & solver ☐ First 3D code in NSC
- ☐ Long-product rolling
  - ☐ Bar / wire, H-shape, rail, angle, slab, pipe, etc.
  - ☐ Versatility for profile/ configuration/ number of rolls
- ☐ Flat rolling
  - ☐ Discretized model of roll deformation for various mill types
  - ☐ High precision of contact analysis for strip shape evaluation
- ☐ Helical rolling
  - ☐ Stable calculation of extremely complex material flow
- ☐ Non steady-state analysis of flat/shape rolling
  - ☐ Inter-pass geometry processor (for plates) ☐ Sizing press
  - ☐ Asymmetric deformation during rolling (for shapes)

*) All rolling codes are composed of pre-processor and solver.

**Fig. 10 Make-up and characteristics of NSCARM**



**a) Distribution of longitudinal stress (pair-cross mill)** **b) Evolution of lateral displacement of strip edge**

**Fig. 11 Examples of analytical results of flat rolling**

## 4. Numerical Simulation of Rolling Processes

Analysis of rolling processes using the finite element method (FEM) is advancing remarkably as a reliable and versatile analytical method that avoids bold hypotheses, which are often involved in the classical methods such as the slab method or the energy method. Process development based on numerical experiments was made possible largely due to the latest rapid advances in computer capabilities at low costs and sophisticated commercial software packages. The following sub-sections present some examples of Nippon Steel's technical developments that apply numerical experiments based on FEM.

### 4.1 Development and application of the general-purpose rolling analysis system NSCARM

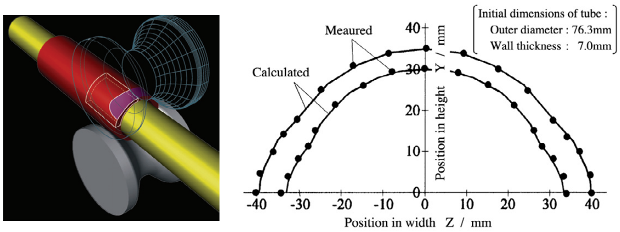
The rigid-plastic FEM was developed as an efficient method for analyzing deformation phenomena consisting mainly of plastic deformation. The theoretical system was established in the early 1970s[20, 21], and it was applied to the analysis of steel rolling (two-dimensional, steady-state analysis[22]) for the first time in Japan in 1979. Nippon Steel initially applied this type of FEM to the development of programs for two-dimensional, asymmetric sheet rolling analysis[23], and then gradually expanded its application to two-dimensional thermo-mechanical analysis of sheet rolling coupled with material structure evolution, three-dimensional pipe rolling analysis, H-shape rolling analysis, sheet rolling analysis coupled with elastic deformation of the roll assembly, shape rolling analysis, skew rolling analysis, three-dimensional thermo-mechanical coupled analysis and three-dimensional, non-steady-state rolling analysis. All of these applications led to the multi-purpose rolling analysis system named the Numerical System for Computer Analysis of Rolling Mechanisms (NSCARM)[24]. The features of the NSCARM can be seen in **Fig. 10**; it covers virtually all commercially used rolling processes.

**Fig. 11** shows an example of sheet rolling analysis. Part a) illustrates, in vertical enlargement, the longitudinal stress distribution in a sheet during hot rolling on a 4-high mill, and Part b) depicts the width change during rolling. These displays quantitatively show that any action of a sheet crown control actuator (a roll bending force, roll cross angle, etc.) changes the stress distribution, which in turn significantly changes the sheet width. Findings of this kind led to the development of high-precision rolling control models. **Figs. 12 and 13** show examples of the analytical results for pipe rolling on a mandrel mill and rail rolling on a universal mill, respectively. These analysis tools made it possible to quantify complicated three-dimensional deformation phenomena during rolling, which proved effective in improving the dimensional accuracy of the products, preventing operational troubles due to bending and twisting of the rolled materials, and thus radically optimizing and stabilizing rolling processes.

### 4.2 Simulation of temper/skinpass rolling

The elastic deformation of rolls and rolled materials exerts significant effects on the temper/skinpass rolling of thin sheets, leading to uneven deformation of the rolled sheets, out-of-round deformation of the rolls and other problems. Classic rolling theories using the slab method, however, cannot explain these phenomena. The mechanisms have not been made sufficiently clear yet, for example, for the phenomenon called jumping, wherein elongation changes discontinuously from below 1% to 4 - 8% during rolling, particularly with bright rolls and the phenomena in rolling with dull rolls, among others.

Facing these problems, Nippon Steel tried to simulate temper/skinpass rolling using MSC.MARC, a multi-purpose software package for finite-element, elasto-plastic analysis, which has sophisticated and high-speed functions, such as elasto-plastic contact analysis. **Figs. 14 to 16** show examples of the analysis results. The



**a)** **Schematic view of analysis region**

**b)** **Cross-sectional shape of rolled tube**

**Fig. 12 Analysis of mandrel rolling of tubes**

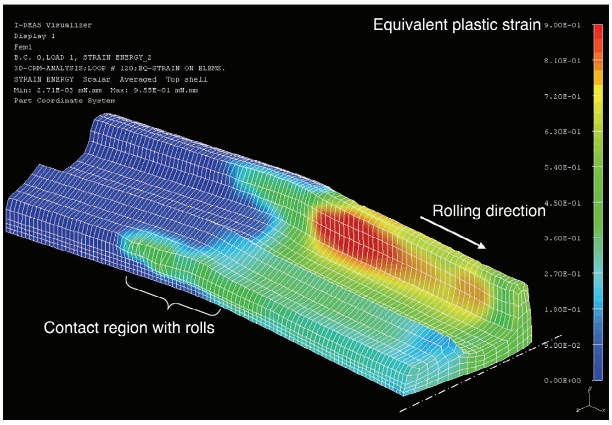


**Fig. 13 Material deformation in universal rolling of steel rail (transient analysis, symmetric in height)**

sophisticated analysis of rolling in consideration of the upper and lower yield points of the rolled material and the elastic deformation of the work rolls enabled a rational interpretation of the phenomena peculiar to temper/skinpass rolling, such as jumping and the effects of roll surface roughness over the rolling operation[25-27].

### 4.3 Simulation of strip behavior on run-out tables in hot strip mills

The run-out table (ROT) at the delivery side of the finishing mill train is an important section of a hot strip mill for determining the material quality of the products by controlled cooling. During rolling, particularly of thin strips, however, the strips are likely to behave unstably; that is, the head end may lift off of the table rollers and fold backwards, or the middle portions may flutter in waves, as shown in **Fig. 17**, which sometimes leads to poor control of cooling and a decrease in productivity.

The unstable strip behavior on the ROT is an extremely complicated and non-steady phenomenon resulting from internal and external forces, both dynamic and quasi-static, such as impact, inertia and elasto-plastic deformation of the strip itself, that are applied simultaneously and instantaneously. Nippon Steel attempted to quantitatively clarify the mechanisms of such dynamic, non-steady and unstable phenomena by using a software package (LS-DYNA) based on the dynamic explicit finite element method FEM, which is often used currently for collision analysis of automobiles and the like, as its first application to the analysis of steel rolling phenomena[28].

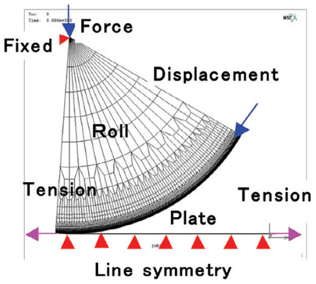


**Fig. 14 FEM model of skin pass rolling**

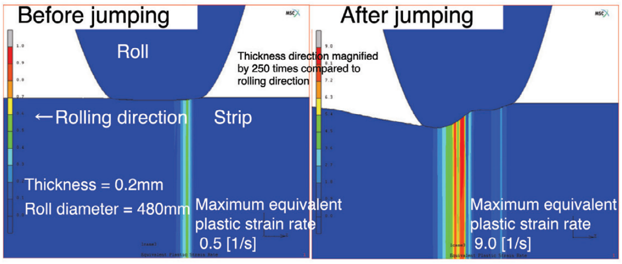


**Fig. 15 Result of skin pass rolling simulation with bright work-roll**

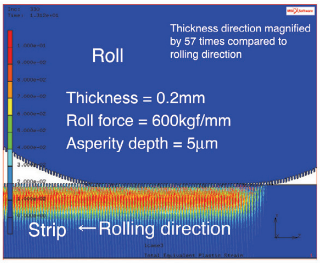
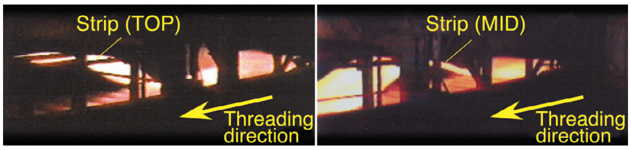


**Fig. 16 Result of skin pass rolling simulation with dull work-roll**



**(a) Flying behavior of front portion of strip**

**(b) Waving behavior of middle portion of strip**

**Fig. 17 Examples of unstable strip behavior during threading at a hot strip mill**

For example, **Fig. 18** shows an analytical result for the behavior of a thin strip on the ROT using this method. The simulation visualized the strip flotation and deformation resulting from the collision of the strip head end with the table rollers and the rebounding and waving of the strip middle portions caused by its sagging between the rollers; these results were found to agree with the strip behavior on real mills.

**Fig. 19** shows an example of a comparison between test and simulation results for strip waving. The simulation analysis yielded numerical information, such as the limit of the strip thickness that

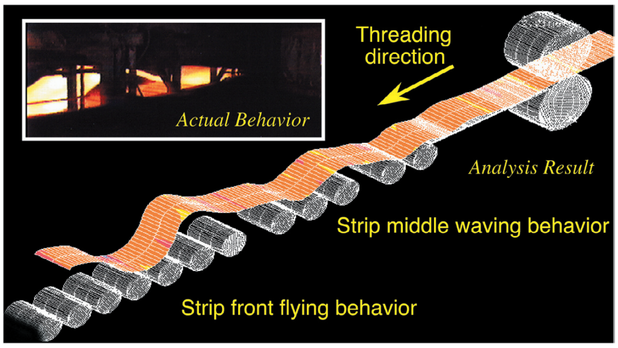


**Fig. 18 Example of result of simulation for unstable strip behavior during threading**

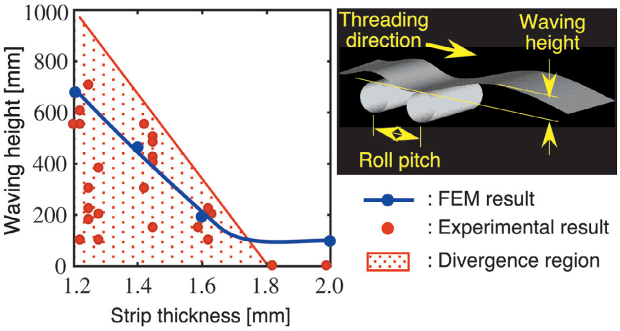


**Fig. 19 Evaluation of waving behavior of middle portion of strip**

causes unstable processing and the strip height above the table rollers during waving.

Technical developments aimed at stabilizing strip processing on the ROT is underway based on these simulation results.

## 5. Reheating Furnace Technology

Combustion and heating technologies for reheating slabs/blooms for hot rolling advanced with the principal aims of achieving energy savings and homogeneous heating. Although a variety of energy saving methods were developed after the oil crisis and actually used in the early 1980s, few of them were really innovative. However, when regenerative alternating combustion technology was introduced from the U.K. in the late 1980s[29], technical developments advanced rapidly in order to make it suitable for commercial use so that it would be possible to take advantage of its excellent energy saving and homogeneous heating performance.

Nippon Steel's technical development efforts for the commercial application of the technology were carried out through close cooperation between the R&D Laboratories, the Engineering Divisions Group (now Nippon Steel Engineering Co., Ltd.) and the steel mills, focusing mainly on (1) studies of the basic characteristics of regenerative alternating combustion[30], (2) clarification of in-furnace gas flow and heat transfer, which are different from those in conventional reheating furnaces[30], and based on the results, technical development for the design of the furnace and combustion equipment[30], and (3) development of sophisticated technology for analyzing in-furnace heat flux to support item (2) above[31]. The regenerative alternating combustion technology that was thus developed was applied, wholly or partially, to more than 20 of the company's reheating furnaces beginning in 1996, significantly contributing to energy savings, the reduction of $CO_2$ emissions, and the improvement of product quality.

## 6. Scale Control

In the steel rolling process, oxide scale that forms on the steel surface has significant effects on the surface quality of steel products, and therefore, adequate control of scale structure is an important technology for improvement of yield and productivity.

Nippon Steel has focused attention on scale properties during hot rolling. The company has established test methods for simulating scale formation in actual rolling processes and studied the effects of alloy elements and atmosphere on scale structure and of scale structure on scale properties during hot rolling process. **Fig. 20**[32] shows some results of tests on the effects of scale structure on the hot shortness of steel products; effective countermeasures against hot shortness were developed based on these results.

In addition to the above approaches, studies that take into account mechanical factors, such as detaching and deformation behavior during the hot rolling process, are considered necessary.

## 7. Technologies for Rolling Rolls and Tools

Both wear resistance and toughness have recently been required for rolling rolls, and in response, the centrifugal casting and continuous pouring process for cladding (CPC), which is capable of combining a tough core with a surface layer of high wear resistance, has been developed and commercially applied, replacing the conventional setting casting method. In the meantime, adamite rolls were used for the former stands of the finishing mill train of hot strip mills, and Ni grain cast-iron rolls for the latter stands. As rolling conditions grew increasingly demanding, however, higher durability was required, and in response, high-Cr cast-iron rolls, in which chromium carbide is formed in fine particles to improve wear resistance, were developed in Europe in the 1970s, and became popular in Japan, too. Later, in the early 1990s, high-C high-speed-steel rolls were developed in Japan; they contained V, Mo, W and Cr, and had high-hardness carbides, such as MC, $M_6C$ and $M_7C_3$, formed in significant quantities. Because the wear resistance is about 5 times that of Ni grain cast-iron rolls and 2.5 times that of high-Cr cast-iron

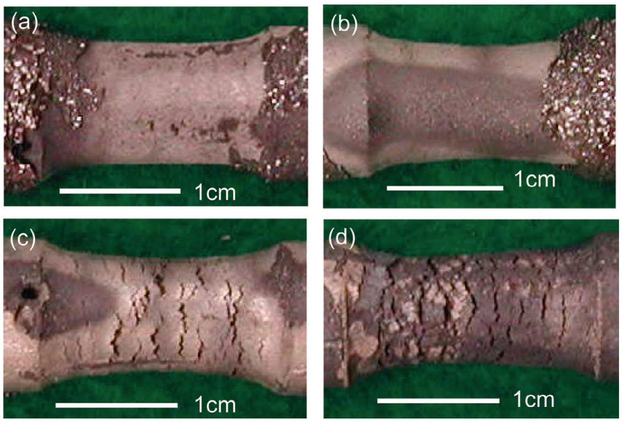


**Fig. 20 Surface appearance after oxidation-tensile tests**
**(a) Low oxidation condition (0%$O_2$), (b) Reference condition (2%$O_2$), (c) High oxidation condition (5%$O_2$), (d) Extremely high oxidation condition (80%$O_2$)**

rolls, the developed rolls are presently used on the former and middle stands of the finishing mill trains of virtually all hot strip mills[33, 34]. The high-speed-steel rolls, however, tend to develop deep cracks at locations where the strip tail crashes when used on latter finishing stands, and thus, they are unsuitable for this use despite their excellent performance. Improvement in crack resistance is the most important issue for wider use of the high-speed-steel cast rolls.

Roughly 20 years after the use of high-speed-steel rolls began, the latest goal is to achieve lower rolling temperatures in order to save energy and obtain higher reduction for the development of new products. A new, higher durability roll is therefore sought that will make these rolling conditions practicable. To improve durability, it is necessary to increase the amount of hard ceramics in the roll material, and presently rolls of fiber-reinforced metal (FRM) containing ceramic fiber to ensure toughness are being developed. In trials run on model mills, such FRM rolls have demonstrated a wear resistance of about four times that of high-speed-steel rolls and a crack resistance of about three times that of the conventional rolls[35].

With respect to tools for rolling, Nippon Steel studied the viability of composite tools, applying a cermet surface coating to the plugs and guide shoes for seamless pipe rolling in order to extend their service life, and actually used them for the rolling pipes of alloy steels[36].

To enhance the durability of rolling rolls and tools, it is essential to optimize the rolling operation, including the use of rolls and lubricants. The improvement of rolls and tools is pursued through clarification of the mechanisms causing surface damage in consideration of the tribological phenomena between the roll and the rolled material[37-39].

## 8. Rolling Lubrication

### 8.1 Lubrication of hot rolling

While a lubricant for hot rolling is required to decrease the friction force in order to minimize roll damage, it is necessary to maintain a friction force to a certain extent in order to avoid slipping when biting at the head end of the rolled material. To balance these mutually conflicting requirements, new lubricants for hot rolling using semi-fluid grease, solid powder lubricants, etc., have been developed to replace conventional fluid lubricants based on mineral oils and esters. A lubricant comprised of grease mixed with a mica powder with a high friction coefficient and potassium phosphate powder that forms molten films at high temperatures was tested on a commercial mill; despite the high content of the highly lubricating grease, this lubricant proved effective in preventing slipping when biting at the head end of the rolled material and significantly reduced roll wear, as seen in **Fig. 21**[40, 41].

In addition to the above, various lubricants containing solid lubricating additives have been proposed and tested to determine their practical effectiveness. One example is a combination of graphite powder, which is effective at minimizing surface damage due to seizure, and a polymer powder[42], which is a slipping-resistant lubricant composed mainly of mica powder having high swelling properties[43]. Other methods have also been tested, including local lubrication using a solid lubricant mixed with wax that is fed to the desired regions[44], and the use of a lubricant containing calcium carbonate to suppress formation of black oxide film on high-speed-steel rolls, thus minimizing banding of the black oxide film[45]. Presently, lubricants for hot rolling are composed mainly of mineral oil, but new lubricating concepts based on solid lubricants or other new additives and innovative lubricating methods are awaited.

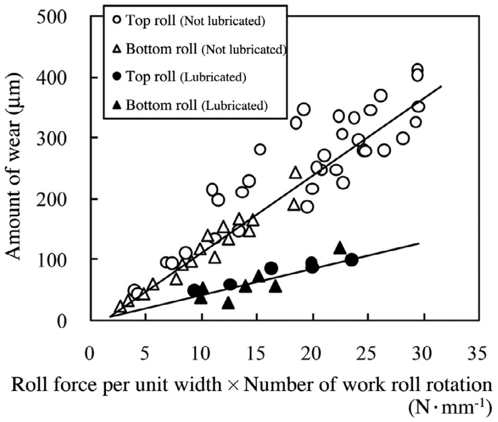


**Fig. 21 Effect of lubrication on work roll wear**

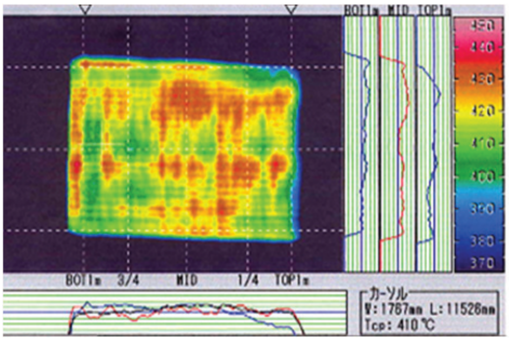
### 8.2 Lubrication of cold rolling

The lubricants conventionally used for cold rolling consisted mainly of beef tallow or fish or vegetable oil, but to improve the cleanliness of the mill equipment and coolant, decrease roll damage and prevent seizure, use of lubricants composed mainly of esters became popular[46-49]. Due to the latest technical developments, the measurement and determination of the degree of oxidation of the oil/fat in the coolant, its saponification number, the ferrous content, and the concentration of the oil/fat are more rapid, which has enabled more stable mill operation[50-53].

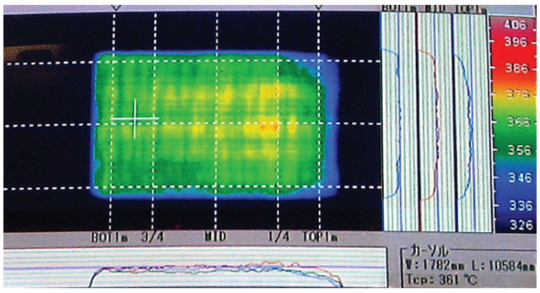
## 9. Cooling of Rolled Steel

Many new methods for cooling steel were worked out for the sophisticated manufacture of high-quality products, and a variety of equipment incorporating the new methods was designed and built, contributing to the manufacture of high-functionality products using different production processes. Innovative cooling facilities were designed and built for the continuous on-line cooling (CLC) process for heavy plates[54], the quenching process for head-hardened rails[55], and so forth during the 1980s. Different types of cooling agents, such as water, gas, etc., were used according to the required product properties.

Nippon Steel developed the CLC process applying unique in-line cooling facilities for heavy plates; this process has enabled the economical production of high-functionality products, and significantly contributed to cost savings for end-user industries[56]. Furthermore, in 2004, an improved version of CLC, named CLC-$\mu$ ($\mu$ (mu) standing for metallurgically universal, ultimate, etc.), was developed in response to the ever increasing demand for higher product functionality and applied to plate mills. With the new process, the temperature difference in a plate after cooling decreased from 50 to 30℃ (**Fig. 22**), significantly improving the temperature homogeneity[57]. New technical developments for continuous hot strip rolling include cooling equipment for slit laminar flow in homogeneous strip cooling after finishing rolling[58] and two-stage cooling for the production of transformation-induced plasticity (TRIP) steel, a new type of high-functionality steel[59]. As stated above, in the area of cooling, process development through software and hardware approaches for the thermo-mechanical control process (TMCP) in combination with rolling, and closely linked with product development, is beginning to bear fruit. We are determined to promote



(a) Temperature distribution after CLC



(b) Temperature distribution after CLC- $\mu$

Fig. 22 Temperature distribution after plate cooling process

further technical developments aimed at higher product quality through accuracy enhancement in the control of manufacturing processes.

## 10. Future Prospects

We believe that Nippon Steel enjoys technical advantages in the field of high-grade steels, where the company can meet clients' technically demanding requirements. The company must maintain this competitive edge and stretch its lead further. At the same time, it must also reduce production costs and enhance the productivity of ordinary steels, which account for the bulk of the market.

At present, with world steel demand expanding, advanced technologies are transferred to mill builders, who in turn offer them one after another to the new steel plants being constructed in economically developing countries, turning them into everyday technologies. To maintain our technical lead and expand the gap further, even in the current situation, there is, needless to say, no option but to accelerate development of new technologies that meet the future needs of end users, and take a firm stand on our basic principles. We will try to roughly outline the trends in future rolling technology from this standpoint.

The primary driving force for the development of new rolling processes will be the increasingly demanding requirements for steel products, including higher tensile strength, thinner and wider sheets for flat products, and higher functionality in long products. New products must be introduced in response to these needs, and technical advances that will enable rolling of such new products at high yield and productivity will be realized beyond the capability of existing processes.

**<Appendix> Achievements concerning rolling technology awarded by Okouchi memorial foundation (relevant to current article)**

| Fiscal year | Category | Title | Corresponding sections |
|---|---|---|---|
| 1986 | Memorial Grand Prize | Development of high precision and schedule free rolling technology for a large scale hot strip mill | Crown control (Section 2.3, Section 3.2) |
| 1990 | Production Grand Prize | Development of efficient and flexible rolling technology for H-shapes | NITTETSUHYPER BEAM® (Section 2.4) |
| 1996 | Production Prize | Development of high precision and efficient strip rolling technology with a pair-crossed roll mill | Pair-crossed roll mill, absolute gauge-meter AGC (Section 2.3, Section 3.1) |
| 1997 | Production Prize | Development of high-speed-steel rolls made by continuous pouring process for cladding | High-speed-steel roll, CPC method (Chapter 7) |
| 2000 | Production Prize | Development of endless rolling technology for hot strip mill and new products | Endless hot strip rolling (Section 2.2) |

The development of rolling technology will be supported by the fundamental technologies of computerized control, numerical analysis, heating, scale control, manufacture and use of rolls and tools, rolling lubrication, cooling, measurement, etc. Advances in these fields may trigger significant innovation in a wide range of areas. In addition, computerized control and numerical analysis are expected to advance further as the capabilities of computers and the sophistication of analysis theory continue to improve. Heating technology is responsible for energy savings, decreases in $CO_2$ emissions and product quality improvements. For scale control, the understanding of surface phenomena and the use of simulation methods will have to be expanded, and as stricter standards are applied to product surface quality, further technical advances and greater improvements in quality are expected. Development of new roll, tool and lubrication technologies is desired for improving productivity and product quality under increasingly tough rolling conditions. In order to incorporate desired properties into new products, advances in steel cooling are expected to provide a better temperature control capacity, and thus an improvement in the temperature homogeneity at cooling and wider flexibility.

Although seemingly mature, rolling technology is expected to achieve yet further developments and advances, and therefore, we have to focus our efforts on making such advances a reality.

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