

# Technical Progress of Stainless Steel and Its Future Trend

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## Abstract

*In response to a steady increase in demand, stainless steel production has grown at an average annual rate of five percent over the last ten years. In the meantime, manufacturing technology for the product has advanced to offer higher-performance products to the market at lower costs, and as a result, product quality has been enhanced, manufacturing efficiency has improved, and capacity increase and integration of production equipment have advanced significantly. New steels with higher functionality such as high-purity ferritic and dual-phase stainless steels have been developed and entered commercial production backed by advances in manufacturing technology. This paper presents an overview of previous advances in stainless steel manufacturing technology, and what is required in the future.*

## 1. Introduction

In 1958, more than half a century ago, Sendzimir-type 20-high mills were first built in Japan and mass production of wide cold-rolled stainless steel strips began. Ever since, the demand for stainless steel products has grown steadily as the country's economy grew. Beyond Japan, the demand for stainless steel has been growing dramatically lately in China and other Asian countries in line with their economic growth. In addition, spurred by the increasing awareness worldwide of environmental issues, the use of stainless steel products has expanded. Examples of new applications include automobile exhaust systems, in which vapor temperatures are becoming higher and higher, as well as seawater desalination plants and other environment-related uses, which seek to make the most of the heat and corrosion resistance and other excellent properties of stainless steel. On the other hand, in view of the fact that rare earth elements are expected to be in seriously short supply in the long run, new resource-saving and highly functional stainless steels have been actively developed; such as high-purity ferritic stainless steels devoid of Ni, and high-strength dual-phase steels with high corrosion resistance and low Ni content, which already account for a considerable portion of the market, to name but a couple of examples.

In response to the rapidly growing demand and need for mass production of these newly developed steels, stainless steel produc-

tion technology has shown remarkable progress; or it may be more appropriate to say that the rapid growth of the stainless steel market has been made possible by production technology that enabled the economic manufacture of high-performance products and mass production of technically demanding new materials such as high-purity ferritic and dual-phase stainless steels.

This paper presents a historic overview of stainless steel production technology and a perspective of what is required in the future.

## 2. Technical Trends of Stainless Steel Production

### 2.1 Historical overview of stainless steel production

**Figs. 1 and 2** show the production of stainless steel over the last ten years (unless otherwise specified, all measures herein are metric)<sup>1, 2)</sup>. Global production grew over the period at an annual rate of five percent approximately. Whereas stainless steel production has remained nearly unchanged in developed countries like Japan, U.S.A., U.K. and Germany, it increased significantly in countries such as China, South Korea, India, Belgium and Finland. Of these, China demonstrated exceptional production growth backed by its rapid economic expansion and consequent increasing demand for products; annual growth in stainless steel production throughout China in 2000 and thereafter was as large as 45 percent.

Capital investment in stainless steel production facilities is still ongoing in China, and one stainless steel producer there has a capac-

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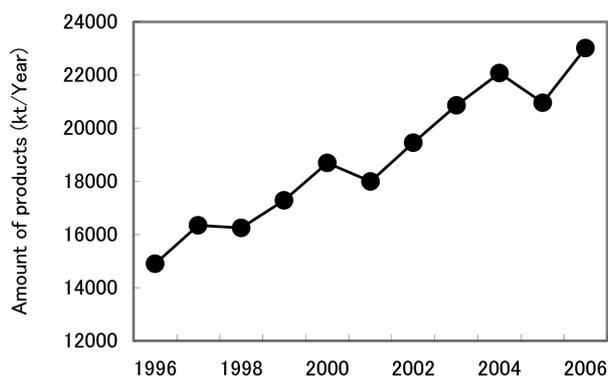


Fig. 1 Global stainless steel production

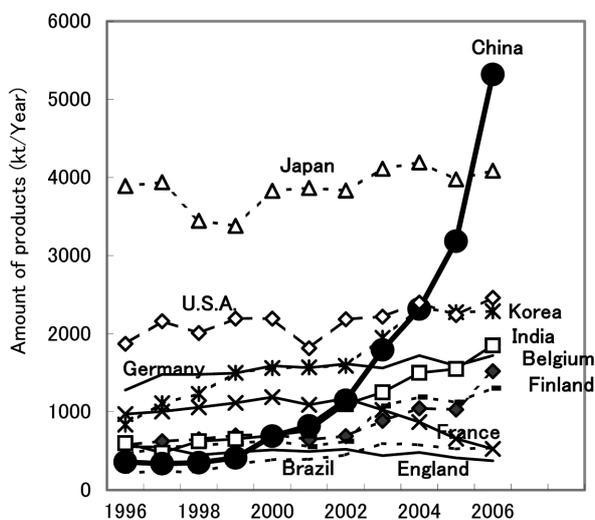


Fig. 2 Stainless steel production in leading countries

ity of some three million tons per year in terms of slab production, nearly equal to that of Japan in its entirety. India has also announced ambitious capital investment plans in this field. Thus, we have to continue to carefully watch the international balance of stainless steel supply and demand, especially in the Asian region.

In Europe, on the other hand, production capacities for individual producers have increased principally through mergers and acquisitions: whereas there were 21 stainless steel manufacturers in 1976 in the region, by 2001, these had been consolidated into four, with production capacities of two to three million tons per year. Huge stainless steel producers with production capacities exceeding two million tons per year also appeared in South Korea and Taiwan. This exemplifies the worldwide restructuring of stainless steel producers that has occurred.

## 2.2 Latest developments in stainless steel production technology

### 2.2.1 Steelmaking

Expensive alloying elements such as Ni, Cr, Mn, Mo, etc. are consumed in large quantities in the production of austenitic stainless steel, and for this reason, this type of stainless steel is mostly produced by electric arc furnaces (EAFs) from recycled stainless steel scrap. The thermal capacity of electric arc furnaces for stainless steel production, which was mostly 30 to 60 tons in the past, has increased to 90 to 160 tons, and many old furnaces have been expanded to increase production capacity. At the same time, supplementary burn-

ers and oxygen-blowing facilities have become standard equipment for many furnaces to accelerate scrap melting, as well as aluminum conductor frames to decrease power consumption. These are specific examples of the efforts to enhance productivity and reduce costs in steelmaking processes.

In the refining process of stainless steel, Cr is one of the main alloying elements, but it hinders the activity of C, making it difficult to decarburize steel; especially in the low-C range, Cr is oxidized in priority hampering decarburizing reactions. The history of stainless steel smelting technology is essentially that of the development of methods to effectively decarburize steel while preventing oxidation of Cr. The argon-oxygen decarburization (AOD) and vacuum-oxygen decarburization (VOD) processes, their combination (the AOD-VOD process), and the combination of a converter and the VOD process (the converter-VOD process), are the fruits of these development efforts. The EAF-AOD and converter-VOD processes now account for the major part of stainless steel production. Of these, the converter-VOD process was instrumental in the development of high-purity ferritic stainless steels.

The AOD process is superior to the VOD in efficiency and in being capable of decarburizing from a high-carbon range, but its decarburization rate decreases and fluctuates significantly in the low carbon range, and the carbon content attained is higher than that by the VOD process. In addition, while oxygen is blown in during VOD, it is necessary to inject  $N_2$  or Ar as diluting gas together with  $O_2$  to decrease the partial pressure of CO, but this is costly especially when the gas volume is high. The V-AOD process (also called the vacuum converter refiner, or VCR)<sup>2)</sup> was developed by Daido Steel Co., Ltd. in 1991 as a process combining the advantages of AOD and VOD.

The V-AOD process is a low-oxygen decarburizing process wherein vacuum facilities are added to an AOD furnace, and carbon content is decreased at low pressure utilizing oxygen solute in steel and oxides in slag without injecting oxygen, taking advantage of the strong stirring effect of the AOD process. Nippon Steel & Sumikin Stainless Steel Corporation (NSSC) introduced the V-AOD process to its Hikari Works in 1996, and in 2001 developed a low-pressure, accelerated decarburizing process whereby the furnace pressure is decreased from a mid-carbon range ( $[C] = 0.6\%$ ) and steel is decarburized with oxygen blown in without injecting diluting gas. Using this process, NSSC achieved a significant improvement in oxygen consumption, leading to a remarkable decrease in both processing time and consumption of silicon, used as a decarburizing agent. Fig. 3 schematically illustrates the processing stages of the low-pressure, accelerated decarburizing using the V-AOD process. Whereas when using the conventional VOD process, it was necessary to mix a diluting gas with oxygen blown in from the bottom in the carbon range of 0.6 to 0.1 percent, with the V-AOD process, no diluting gas is required thanks to the low furnace pressure, and thus high oxygen efficiency for decarburizing is obtainable.

In addition to the EAF-AOD and converter-VOD processes mentioned earlier, a steelmaking process using a smelting-reduction (SR) furnace, a decarburizing (DC) furnace and a VOD furnace, called the SR-DC-VOD process, has been developed and used for commercial production<sup>3)</sup>; this process is characterized by use of Cr ore instead of metallic Cr.

For future development of steelmaking processes, it is necessary to adopt a broad view covering recycling of raw materials and waste. While a carefully elaborated recycling system covering the collection routes of steel scrap has been established for general-purpose austenitic stainless steel, no such system is in place for new stainless

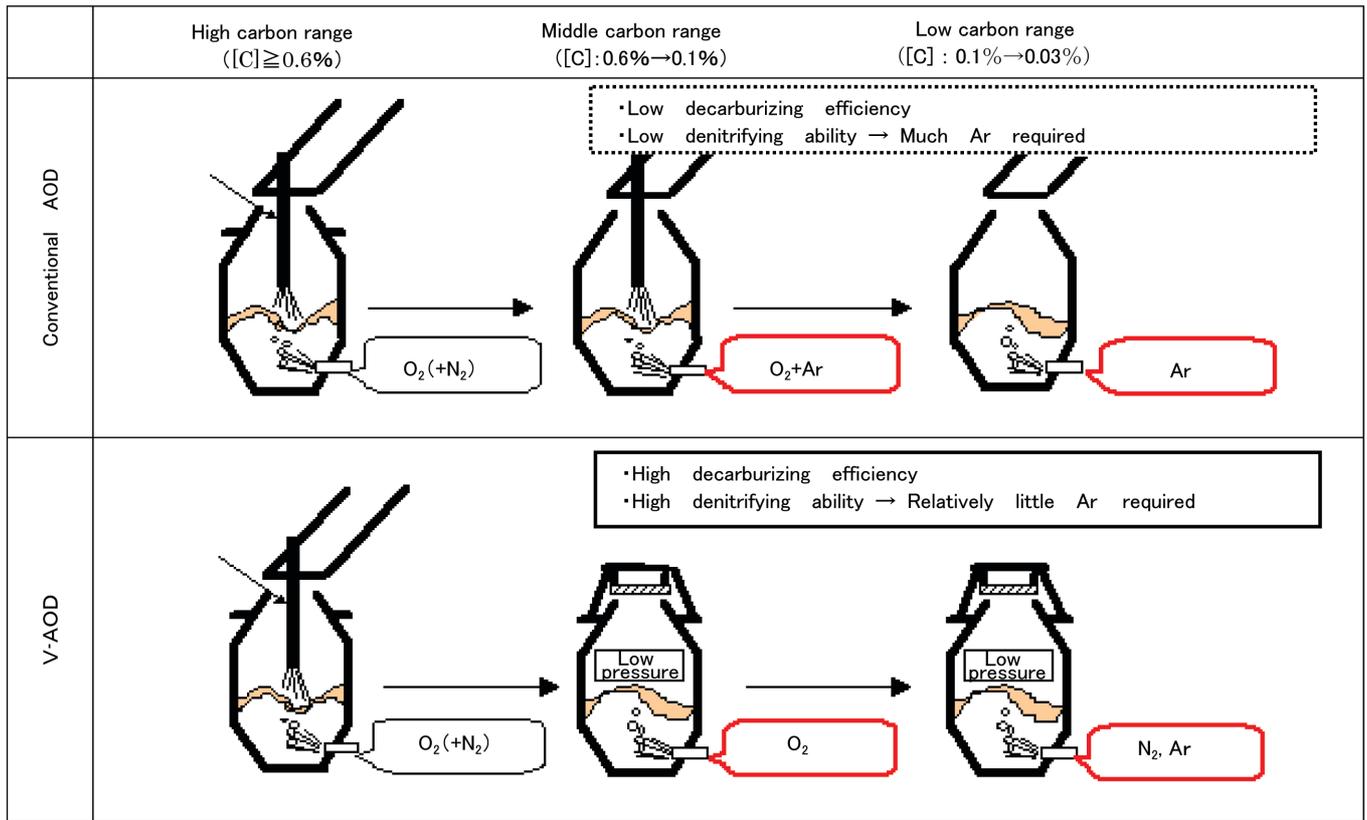


Fig. 3 Schematic illustration of V-AOD process

steels now under development and those for which applications are being developed; these new steels include resource-saving type steels such as ferritic, dual-phase stainless steels as well as low-Ni, high-Mn steels commonly known as the 200 series steels.

Since the 200-series steels are not magnetic, like other austenitic stainless steels, no magnetic classification is applicable, and their scrap may easily be mixed with those of common austenitic steels, causing degradation of scrap quality and possibly jeopardizing the stainless steel waste recycling system. Another important issue requiring more emphasis from the viewpoint of zero emissions is the recycling of slag, scale, dust and sludge as side products of stainless steel manufacturing processes.

2.2.2 Hot rolling of sheet products

Hot-rolled stainless steel sheets are produced using two types of rolling mills: tandem hot strip mills designed for ordinary carbon steel, and Steckel mills exclusively for stainless steel. Tandem hot strip mills were, and are still being, constructed in numbers in China and some other countries, and many of these latest hot strip mills have quality improvement measures such as coil boxes.

Although inferior in productivity to a tandem hot strip mill, a Steckel mill requires smaller capital investment and offers wider freedom in rolling operation since the number of passes can be selected as desired because of reversing rolling, and in view of these advantages, many stainless steel sheet manufacturers opt for this type of mill. In order to significantly improve the accuracy of strip thickness and crown, some of the latest Steckel mills have the dynamic pair-cross function, whereby the centerlines of the upper and lower sets of work and back-up rolls are crossed with each other at angles changeable during rolling. The recently developed on-line roll grinder

system is effective in preventing local wear of work rolls, which problem is serious especially with Steckel mills<sup>4</sup>.

2.2.3 Cold rolling of sheet products

In 1958, Nisshin Steel Co., Ltd. (then called Nippon Teppan) introduced 20-high Sendzimir mills for cold rolling of large-width stainless steel strips for the first time in Japan, resulting in a remarkable improvement in productivity. In consideration of the significant work hardening austenitic stainless steel, mono-block type Sendzimir mills, which use small-diameter work rolls and are capable of applying heavy reduction, were widely used at that time. Then, many Japanese stainless steel manufacturers introduced 12-high cluster mills of a split-housing type around 1990, for better shape control capacity, easy automatic operation and higher rolling speeds. NSSC also constructed this type of cluster mill at Kashima Works in 1992 (rolling speed 1,000 m/min) and another at Hikari Works in 1993 (rolling speed 1,200 m/min); their rolling speeds are amongst the highest in the world.

On the other hand, various improvements have been introduced to Sendzimir mills: the conventional single As-U shape control mechanism was renovated into the double As-U mechanism and the flexible shaft backing assembly (FSBA) (see Table 1<sup>5</sup>); a split housing design was introduced; and the maximum rolling speed was increased to 1,000 m/min. Table 2 shows popular types of cold-rolling mills for stainless steel sheets and their characteristics<sup>6</sup>.

Lubricant is an important factor in the cold rolling of stainless steel. Presently, neat oils are widely used to obtain lustrous surfaces characteristic of the product. To obtain good luster, it is necessary to maintain thin oil films on the strip surfaces during rolling, but the oil films break locally under heavy rolling loads at high speeds, leading

to heat scratching and poor and uneven luster. In view of this, rolling lubricants suitable for high-speed rolling are being developed employing measures such as the addition of long-chain, dibasic dimethyl ester or suchlike capable of maintaining good lubricating properties at high temperatures<sup>7)</sup>. In order to increase rolling speed further, however, better resistance to heat scratching is indispensable, and it is necessary to develop emulsion lubricants with high cooling capacities.

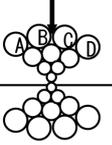
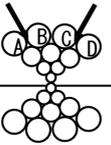
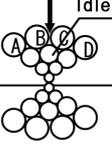
NSSC's Hikari Works developed a soluble rolling lubricant<sup>8)</sup>, and by adequately controlling the size of colloid in the developed emulsion lubricant, successfully manufactured high-luster stainless steel sheets at high speed under a heavy rolling load for the first time in the world; the rolling speed of 120 m/min at Hikari's No. 4 Cluster Mill is the world fastest for a reversing cold-rolling mill for stainless steel. Fig. 4 compares the luster of stainless steel sheets cold rolled with neat and emulsion lubricants. The graph shows that it is possible with emulsion lubricant to obtain surface luster comparable to that obtainable with neat-oil lubricant.

Since the late 1980s, more emphasis has been placed on the environmental friendliness of cars and higher performance of their engines, and in this context, use of stainless steel for exhaust systems expanded rapidly. Higher workability is now required of these mate-

rials in consideration of the complex product shape, especially of exhaust manifolds, etc. In response, parallel with development of new steels, the tandem process, cold rolling of stainless steel using a tandem cold mill for common carbon steel with large-diameter work rolls, has been developed to improve workability and other material properties while reducing costs<sup>9)</sup>. This new process spurred rapid expansion of the use of ferritic stainless steels for automotive components.

With respect to the annealing and pickling processes, the annealing temperatures for stainless steel are higher than those for common carbon steel, and therefore, a longer descaling section is necessary to remove the scale that forms during annealing. For this reason, in terms of a capacity increase in the annealing and pickling line for hot-rolled strips (HAP line), in addition to an increase in furnace capacity and enhanced heating efficiency, high-performance abrasive brushes and longer pickling tanks have been introduced to increase the mechanical and chemical descaling capacities. With respect to the chemical descaling capacity of a HAP line, while the use of sulfuric acid and a mixture of nitric and hydrofluoric acids for the pickling baths remains unchanged, a highly efficient acid recovery system has been effective in stabilizing the pickling capacity, and

Table 1 Schematic illustration of flatness control system

Conventional single As-U	Double As-U	FSBA & SIR
		
As-U on BC	As-U on AB & BC	FSBA As-U on BC and SIR for top idle roll

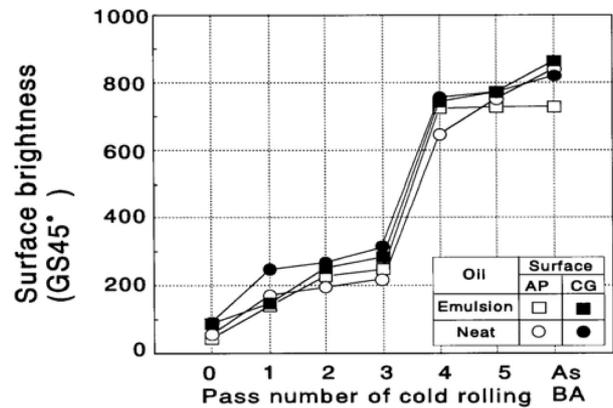
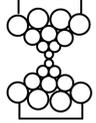
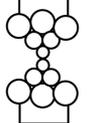
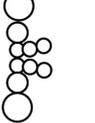
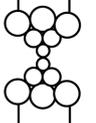


Fig. 4 Surface brightness (emulsion oil and neat oil)

Table 2 Type and characteristics of cold-rolling mill for stainless steel

Type	Sendzimir mill	KST mill	KT mill	UC mill	CR mill
Supply	Sendzimir (Mitsubishi-Hitachi)	KOBELCO	KOBELCO	Mitsubishi-Hitachi	Mitsubishi-Hitachi
Roll configuration					
Characteristics	Flatness control function	•As-U •1st IMR lateral shift	•As-U •IMR lateral shift	•As-U •IMR lateral shift	•IMR taper shift •IMR bender •WR bender
	Gage control function	Hydraulic drive eccentric control	•Wedge-type hydraulic roll-gap control •Electric tilting control	•Wedge-type hydraulic roll-gap control •Electric tilting control	•Hydraulic cylinder •Hydraulic tilting control
	Housing construction	Mono-block housing	Four column separate housing	Four column separate housing	Split housing
	Work roll diameter	Extremely small	Extremely small	Small diameter	-
	Drive	2nd IMR	2nd IMR	IMR	IMR

new technologies such as turbulence pickling using forced cross flows in pickling tanks and spray pickling are being employed to increase capacity. Some new HAP lines, not restricted by space limitations, have a processing capacity of as much as one million tons per year or so.

Higher efficiency is pursued with respect also to finishing annealing and pickling (FAP) lines. Fig. 5 shows the years of construction and the processing speeds at the center section of some FAP lines; it is clear from the graph that the later the year of construction, the higher the line speed. The increase in the processing speed of FAP lines was made possible by advances in heating control and descaling technologies. In the field of heating control, using newly developed quick-response impinging burners, NSSC's Kashima Works commercially applied the direct flame heating method to commercial production<sup>10</sup>. Fig. 6 shows the structure of an impinging burner.

It is essential for a FAP line to de-scale steel strips without damaging the surfaces, and for this reason, it is necessary to change the oxide scale that has formed on the annealing furnace to a water-soluble component. Conventionally, this was mainly done through a salt bath, but as the line speed increased, the Ruthner process, which afforded easier operation, became more popular (see Fig. 6). It has to be noted, however, that the Ruthner process cannot reform silicon oxide, and consequently, descaling performance is severely diminished when processing strips with special chemical compositions such as high-silicon stainless steels. To resolve this problem, NSSC built a Ruthner section at the exit from the salt bath of its FAP line at Kashima Works, and as a result, a line speed of 70 m/min has been maintained without being restricted by steel chemistry. However, to respond to the need for higher descaling speeds and processing of a

wider variety of steel grades, more efficient descaling processes are sought.

Another technical trend worth mentioning is integration of process steps for cold-rolled sheets, which is seen with major stainless steel producers in the West as well as in Asia. There are different types of process integration. In the first type, to improve the efficiency and yield of cold rolling, several cold rolling mill stands with small-diameter work rolls were combined into a tandem mill train; a typical example is the tandem Sendzimir mill of Nisshin Steel's Shunan Works commissioned in 1969<sup>11</sup>. In the second type, a skin pass mill and a tension leveler are incorporated in an FAP line<sup>10, 12</sup>, with most of the FAP lines constructed in Japan in 1989 and thereafter having this configuration. In the third type, annealing and cold rolling processes are integrated to form a continuous processing line for high-efficiency production of stainless steels for general applications. This kind of integration is subdivided into two types: integration of up-stream processes from HAP to cold rolling<sup>13</sup>, and that of down-stream processes from cold rolling through annealing, pickling, skin pass rolling to tension leveling.

Fig. 7 schematically shows the integrated annealing, pickling line of Outokumpu<sup>14</sup>, named the RAP Line, where cold rolling on a 3-stand tandem mill, annealing, pickling, skin pass rolling and leveling are integrated into one continuous line. Another similar example is the recently built continuous processing line of LISCO, China, where cold rolling on a 3-stand tandem mill, annealing, pickling, skin pass rolling and tension leveling are combined continuously<sup>15</sup>.

As stated earlier, many of the latest skin pass mills (SPMs) are integrated in the delivery sections of high-speed FAP lines<sup>10, 12</sup>. With either an in-line or off-line skin pass mill, dry rolling on a 2-high mill with large-diameter work rolls has been the mainstream practice to obtain lustrous surfaces characteristic of stainless steel. For off-line skin pass rolling, the latest mill design trend is reversing rolling on a convertible 2/4-high mill and wet/dry rolling. The No. 2 SPM at NSSC's Hikari Works commissioned in 1990 is unique in that it is a 6-high UC mill, has the world's largest skin pass rolling capacity with a maximum rolling speed of 700 m/min, and has an excellent flatness control function.

As described above, the development of production technologies for cold-rolled stainless steel sheets has mainly focused on mass production of steels for general applications at the lowest cost possible. However, as stated in Section 1, the market also typically began to demand highly functional stainless steels such as high-purity ferritic and dual-phase steels, each in comparatively small quantities. Therefore, technical development, which has mainly focused on enhancing the productivity of commodity steels, will have to place more emphasis on efficient production of technically demanding steels in small lots.

2.2.4 Plate rolling

Recent topics in the field of stainless steel plate production have included the development of new products and improvement of plant operation technologies mainly related to the production of the developed products, with such new products including high-N-content 316L steel for chemical tanker applications and super stainless steel NSSC270 for use in highly corrosive environments. Production technologies that have demonstrated significant advances in recent years include, specifically, improvement of hot workability through steel chemistry design and content control of individual alloy elements, a reduction in tramp elements, slab soaking, etc. and the stable manufacture of high-strength materials through the thermo-mechanical control process (TMCP). Alloy elements indispensable for stainless

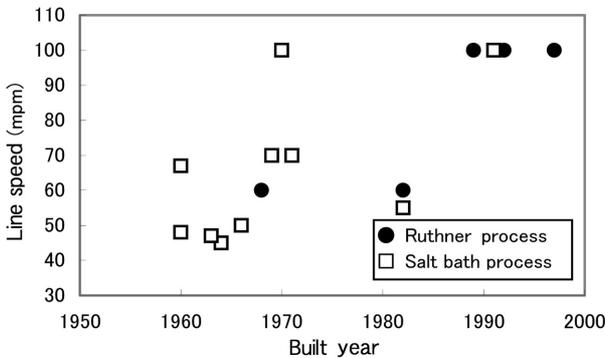


Fig. 5 Processing speed of FAP lines

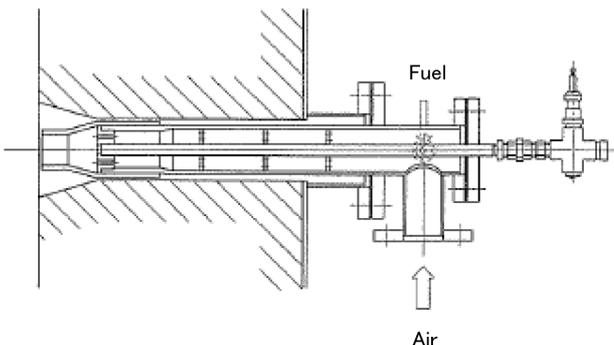


Fig. 6 Structure of impinging burner

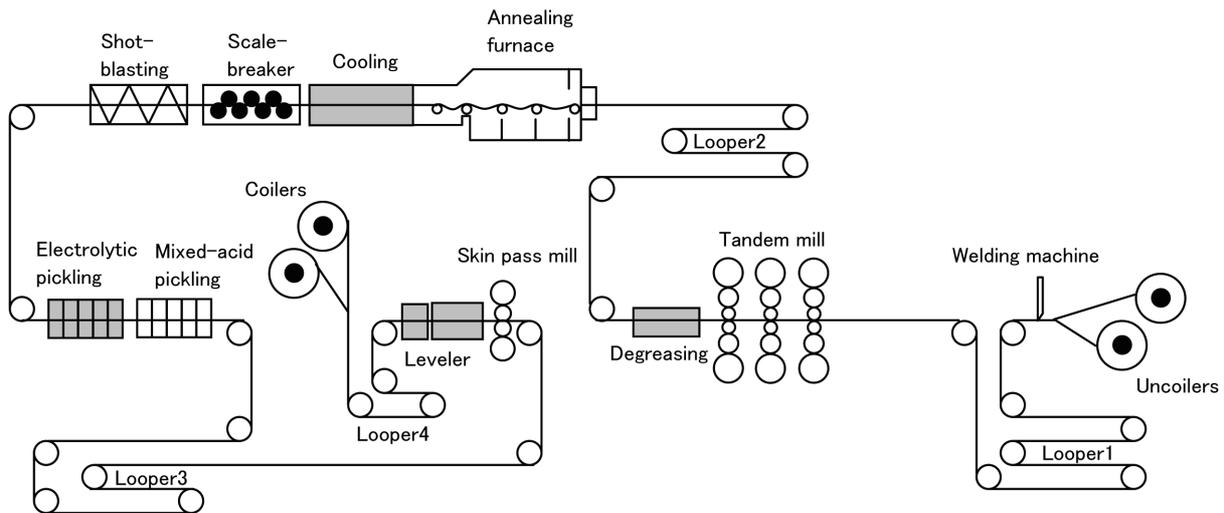


Fig. 7 Schematic configuration of integrated RAP line (Outokumpu)

steel production, such as Cr, Ni and Mo, are expected to be in short supply in the future. In consideration of this, one of the most important technical trends in the field of stainless steel plate production is switching to new low-cost and high-relative-strength materials that can sustain the present performance of the product. Expanding the applications of dual-phase steels is a typical example of such a technical trend, and actually, there is a specific move towards improving the descaling capacities with a view to increasing the production of dual-phase steels.

In the consumer market for stainless steel plates, the size of plant facilities and transport vessels made of stainless steel is increasing, and consequently, the need for larger-sized plates to decrease the fabrication costs for welding and other work is becoming ever stronger. NSSC has established a manufacturing framework for plates up to 200-mm thick and 4,000-mm wide using the 4-high plate mill at Yawata Works exclusively operated for stainless steel, and has effectively responded to the demands and requirements of all consumer sectors. In stainless steel plate production, further technical development is expected in the size increase of manufacturing equipment, capacity increase for high-strength products, development of production technology for technically demanding new materials, namely those more difficult to work, pickle, etc. or requiring stricter dimensional tolerance or higher surface quality.

2.2.5 Wire rod rolling

After shipment from a steel works, wire rods undergo various secondary working steps such as drawing, forging, cutting, heat treatment, etc. at specialist plants to become final products. The hot rolling processes of stainless steel wire rods at a works used to be as follows: breakdown rolling of blooms into billets; roughing, intermediate and finishing rolling of billets into wire rods; and off-line solution heat treatment. Over the last few years, advanced technologies such as direct rolling from blooms into wire rods and in-line heat treatment have been included in commercial production practice. NSSC was one of the first stainless steel producers to introduce helical rolling mills (HRMs) capable of applying a heavy reduction in one pass to the roughing mill train of its wire rod mill line at Hikari Works. On the other hand, the company developed an in-line heat treatment process, and by combining it with the HRMs, brought the direct rolling and in-line heat treatment into commercial opera-

tion.

Fig. 8 schematically shows an HRM. Three conical rolls are arranged helically, and each of the rolls turns to reduce the rolled material while revolving around it, keeping its position relative to the others. This configuration enables application of a heavy reduction per pass and a heavy strain to the surface layer of the rolled material. The heavy working of the surface layer accelerates recrystallization of the texture and thus increases the ductility of the material at subsequent rolling passes, which is effective in preventing cracking and wrinkles due to coarse crystal grains. Presently NSSC manufactures all the wire rod products through direct rolling, enjoying the advantages of a shorter lead time and lower costs.

The in-line heat treatment mentioned above, also known as direct solid solution treatment (DST), is a technology to apply controlled cooling to hot-rolled wire rods that takes advantage of its sensible heat; it replaces solution heat treatment, and thus, is effective for raising production efficiency and saving energy.

In the later stages of wire rod rolling, the latest technical trend is to provide a high-rigidity, high-functionality block mill before or after a finishing mill train. The block mill is effective for better product size accuracy, size-free rolling and controlled rolling and cooling for material quality control. High-rigidity, high-functionality block mills have been introduced to the stainless steel wire rod mill of Daido Steel<sup>16)</sup>, as well as various other similar mills overseas. NSSC

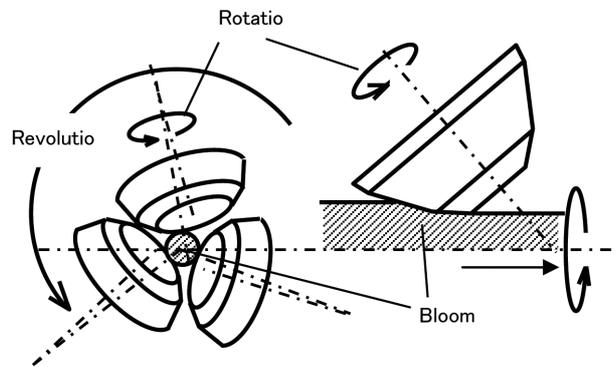


Fig. 8 Schematic illustration of HRM

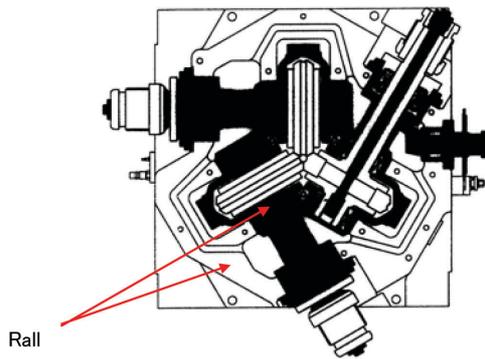


Fig. 9 Schematic illustration of 3-roll stand used in RSB

also built a reducing sizing block (RSB) in 2002 (see Fig. 9). The 3-roll, 4-stand RSB is a precision rolling mill characterized by less flattening of material during rolling than by mills with a two-roll configuration, and is capable of realizing an ovality (difference between diameters measured in different directions) of 0.15 mm or less. The four stands are driven individually, and the roll screw-down can also be controlled individually, enabling size-free rolling, whereby wire rods of various sizes can be rolled without having to change rolls. When it is necessary to change the rolls because of roll wear or a large change in product size, the down time is minimal thanks to the quick changing with pre-assembled spare stands, which has proved effective in significantly improving productivity.

### 3. Summary

Production technology of stainless steel has developed to enable manufacture of stainless steel products of better properties at lower costs in response to growing demand. While the demand for stain-

less steel products and their applications are expected to expand yet more in the long run, with new steel materials having specific functionality, such as high-purity ferritic and dual-phase steels, accounting for a good part of that expansion. This means that a wider variety of products will have to be produced in smaller lots, and technically demanding products will account for a larger proportion of all production. Therefore, besides aiming for efficient mass production of products for general applications as in the past, the technical development of the stainless steel industry will have to focus on efficient production of technically demanding highly functional products in small lots. Another important aspect is the development of recycling technologies for stainless steel scrap and waste arising from the stainless steel industry itself. This will be fundamental to maintaining and strengthening the material's advantage of excellent recyclability.

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