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Technological Progress and Future Outlook for Stainless Steel

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Abstract:

Now that global demand for steels has peaked, stainless steel demand and production are rapidly growing. Despite their high prices, the value of stainless steels is well recognized, and their manufacturing cost has been substantially lowered by the development and improvement of manufacturing technology and as new types have been formulated to meet specific applications. Amid mounting calls for the protection of the global environment and the amelioration of working environments, stainless steel production and demand are expected to increase further. To sustain this trend, it will be necessary to cut manufacturing costs further, develop new grades, and establish accompanying application technologies. The developmental history of stainless steels and stainless steel manufacturing technologies is reviewed, and the general future outlook is described.

1. Introduction

Nearly 50 years have passed since the mass production in Japan of stainless steel sheets and strip started in 1958. Coupled with remarkable advances in manufacturing technology and equipment, stainless steel production and demand have continued to expand phenomenally during this time. Adding chromium to iron improves iron's corrosion resistance. The history of manufacturing stainless steels centers on making effective use of chromium and lowering high manufacturing costs. Various types of stainless steels have been developed for specific applications in which unlike for iron, many properties, such as heat resistance, formability, weldability, magnetism, and artistic appearance, are required in addition to corrosion resistance.

The development and application of stainless steels are expected to progress further, as represented by the advances in manufacturing technology integral to carbon steelmaking technology, intensification of automobile exhaust gas regulations as an antipollution measure, recycling of household electrical appliances, construction of maintenance-free dams and weirs, and elimination of coatings and painted surfaces to assure a comfortable working environment. The history and future outlook of stainless steel production and application follow.

2. Changes in Stainless Steel Production Volumes

The changes in Japanese and world stainless steel production since 1960 are shown in **Figs.** 1[1] and 2[2], respectively. The production by shape of stainless steel in Japan appears in **Table** 1. Despite the slump in crude steel production since 1980, the annual growth rate for stainless steel production has reached 14% in

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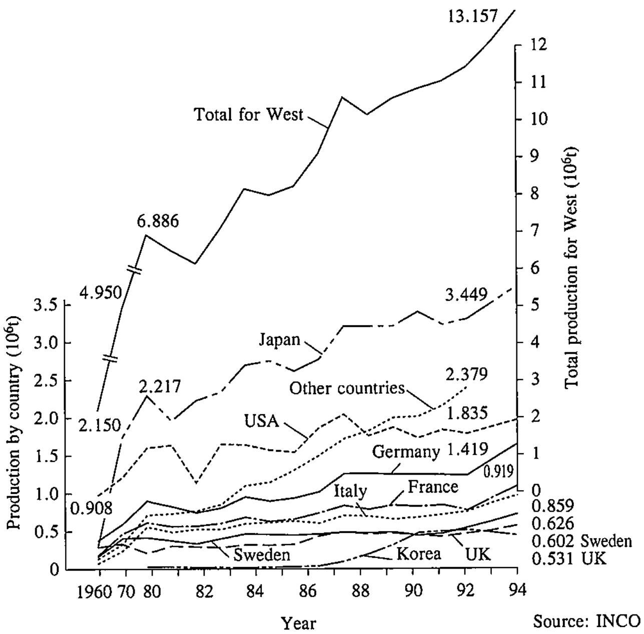


Fig. 1 Crude stainless steel production by country

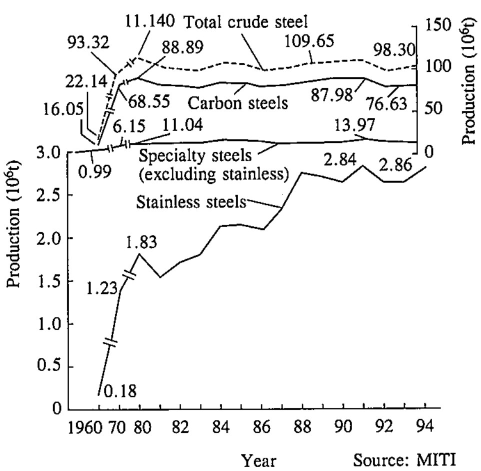


Fig. 2 Changes in total crude steel production and hot-rolled steel production by type in Japan

Table 1 Production by form of hot-rolled stainless steels

(1,000t and %)

Shape	1,984	1,994	Average growth rate from 1984 to 1994
Sheet and strip	1,366	2,008	4.7
Plate	225	232	0.3
Wire	183	282	5.4
Bar	147	156	0.6
Shape	33	56	7.0
Pipe and tube	116	148	2.8
Total	2,071	2,883	3.9
Cr types	654	846	2.9
Cr-Ni types	1,417	2,037	4.4

the Western world and 11% in Japan. Global stainless steel production is expected to expand at an average annual rate of about 5 to 6%, centering on the newly industrializing economies (NIES) and China. By shape, production of sheet and strip, which account for the majority of stainless steel demand, have grown substantially. By market, automobiles, household electrical appliances, and construction have registered large gains, as shown in **Fig. 3**[3]. By type, ferritic stainless steels have made inroads mainly in the automobile and electrical appliance industries, but demand for austenitic stainless steels have increased at a slightly higher rate on the whole.

3. Changes in Stainless Steel Manufacturing Technologies

3.1 Steelmaking

3.1.1 Refining

In stainless steelmaking, it is essential that steel should be efficiently refined by using low-cost raw materials and should be solidified with high yield for good hot workability. Stainless steels differ from carbon steels mainly in that the principal constituent chromium lowers the activity of carbon and is oxidizable especially in the low-carbon region. Various attempts, different from those for carbon steels, have been made to retard chromium oxidation. Edelstahlwerke Witten of West Germany developed the vacuum oxygen decarburization (VOD) process in 1967, and Union Carbide of the United States developed the argon oxygen decarburization (AOD) process in 1968. The VOD and AOD processes supplanted the conventional electric arc furnace (EAF) process and became and have continued to be the world's major stainless steel refining processes. Another vacuum refining process is the RH-oxygen blowing (RH-OB) process developed at Nippon Steel's Muroran Works. **Fig. 4** shows stainless steel production by process, as estimated from existing facilities.

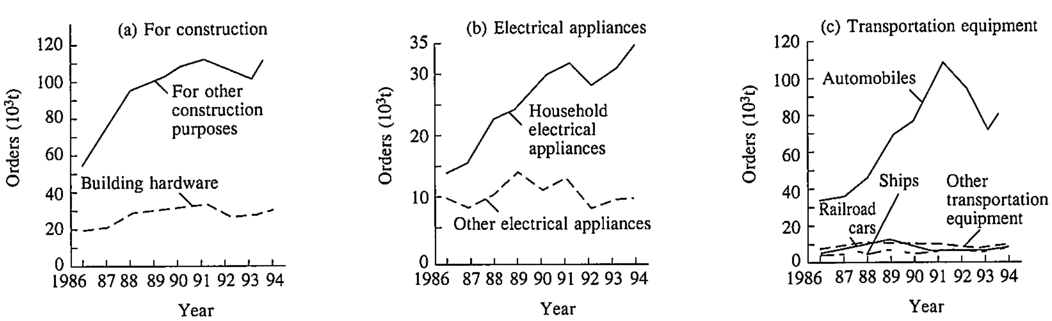


Fig. 3 Changes in flat-rolled stainless steel orders by application

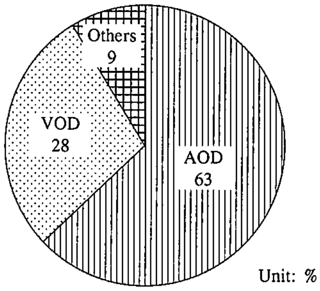


Fig. 4 Distribution of stainless steel production by process

The removal of nitrogen, an interstitial element similar to carbon in ferritic stainless steels, is an especially important refining function in addition to decarburization. Technology development, based on the above two processes, has been pursued to efficiently refine stainless steels to very low carbon and nitrogen levels. Chiefly, such processes are: the strongly stirred-VOD (SS-VOD) process[4] in which argon gas is injected in large amounts through porous plugs in the bottom of a ladle to intensely agitate the heat in the ladle and to refine the heat to very low carbon and nitrogen contents; the VOD-powder blowing (VOD-PB) process[5] in which a powdery refining agent (such as desulfurizer based on iron ore or burnt lime) is top blown onto the surface of the molten steel under reduced pressure to promote carbon and nitrogen removal with the powder introduced into the heat; a process whereby in place of powder, hydrogen gas is blown into the heat; the vacuum converter refiner (VCR) process[6] or an AOD process retrofitted with a vacuum refining function to save on expensive argon gas and to provide very low carbon and nitrogen levels; the Kawatetsu top blowing (KTB) process[7] that is an RH process with oxygen top blowing; and the AOD-VOD process[8] or the combination of the AOD and VOD processes. These processes are summarized in **Table 2**. The combined carbon and nitrogen content is now less than 100 ppm in stainless steels containing 20 to 30% chromium. Besides the reduction in manufacturing costs, the development of more efficient processes is expected with clarification of the effects of carbon and nitrogen on the properties of stainless steels in general and ferritic stainless steels in particular.

An iron ore smelting reduction process is one proposal as an attempt to reduce raw material costs. Prior to the above-mentioned refining stage, inexpensive raw materials, such as nickel ore and chromium ore, are added into a basic oxygen furnace (BOF) or the like, and molten stainless steel is directly made by utilizing the heat from reactions with coke or oxygen. The smelting reduction process must be comprehensively evaluated for waste disposal and other problems in addition to total raw material costs, including yield. It is applied at only a few plants now, but its future development will merit attention.

3.1.2 Casting

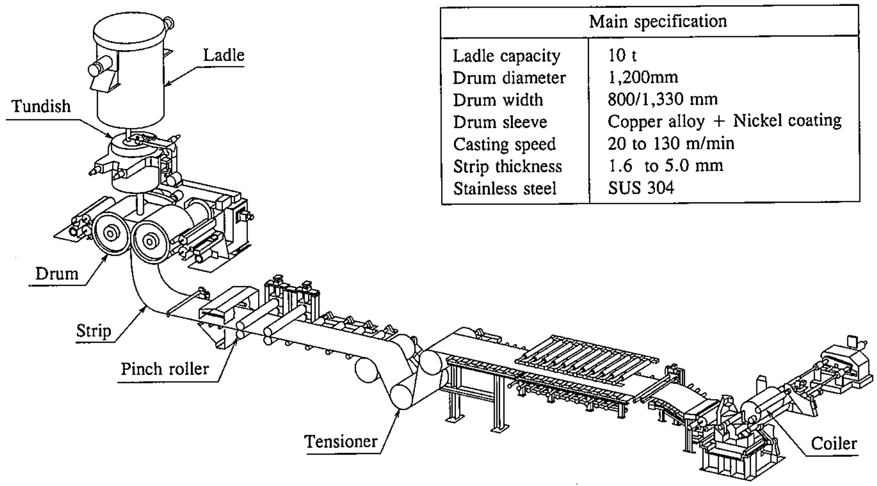
Japan's first continuous slab caster was installed at Nippon Steel's Hikari Works. Stainless steels were continuously cast ahead of carbon steels. This was because stainless steels are more expensive than carbon steels, therefore continuous casting was more cost effective in improving yield, and because SUS 304, a representative stainless steel, was relatively easy to continuously cast. All stainless steels excluding extra-heavy gage plates and some high-alloy grades are now continuously cast, and the continuous casting ratio of stainless steels is estimated at about 99%.

Continuous casting technology was commercialized in the 1960s and is mature now. Various developments and improvements have been made and implemented to date. Among typical examples are: nonoxidation casting for removing inclusions and preventing the formation of fresh inclusions; tundish steel heaters (such as plasma heaters, direct electrode resistance heaters and induction heaters) for keeping the tundish steel temperature constant, promoting the flotation of inclusions, and improving quality; electromagnetic stirring (below the mold and in recent years, in the mold for improving surface quality) for steel solidification structure control to improve formability and segregation; mold powder development and improvement for raising steel surface quality and preventing the carburization of ultralow-carbon steels; sequence casting for boosting efficiency and yield; and variable-width molds.

Initial vertical-type continuous casters developed into vertical-bending (S type) and bow-type machines, and horizontal casters were also developed. Horizontal casters are now used mainly for mass producing blooms for wire and tubular products. Machines for casting 25 to 50 mm thick slabs, instead of conventional 150 to 250 mm thick slabs, have been recently developed and are in use, primarily in the United States and Europe. The strip caster is attracting particular attention as an innovative continuous casting technology for producing hot coils directly from molten steel while bypassing the hot rolling stage. The principle of strip casting had already been considered when the idea of the present continuous caster was conceived, but had not been put into commercial operation for about 100 years because of the nondevelopment of the necessary edge molten steel holding and control technology. Work on the development of strip casting was carried out, centering in Europe, the United States, and Japan. In 1996, plans were announced for the installation of commercial strip casters at Nippon Steel's Hikari Works and Sumitomo Metal Industries' Naoetsu Works. These strip casters are scheduled to start mass production in 1997 to 1998. **Fig. 5** schematically illustrates a twin-drum strip caster[9]. The strip caster planned by Nippon Steel is designed to produce austenitic stainless steel coils, measuring 2.0 to 5.0 mm thick and 1,330 mm wide. The quality of strip-

Table 2 Main stainless steelmaking processes

Process		Main benefit			Purity level (18Cr steel, ppm)			Ref.
		Efficiency	Cost	Purity	[C]	[N]	[C+N]	
VOD	SS-VOD	—	—	○	≦20	≦50	≦70	4)
	VOD-PB	—	—	○	32	48	80	5)
	VOD-H_2 blowing	○	○	—	—	—	—	
AOD	VCR	○	○	○	20	60-80	80-100	6)
AOD-VOD		○	—	—	—	—	—	
RH	RH-OB	○	○	—	—	—	—	
	KTB	○	○	○	—	—	—	



Main specification	
Ladle capacity	10 t
Drum diameter	1,200mm
Drum width	800/1,330 mm
Drum sleeve	Copper alloy + Nickel coating
Casting speed	20 to 130 m/min
Strip thickness	1.6 to 5.0 mm
Stainless steel	SUS 304

Fig. 5 Schematic illustration of twin-drum strip caster

cast products is equivalent to that of conventional strip products. The grain refinement achieved by rapid solidification is expected to provide grindability and other properties superior to those of conventional strip products. Strip casting is under development by many companies and institutes in Japan and abroad as near-net shape casting technology aimed at saving energy and labor and at shortening the production lead time by eliminating the number of necessary process steps. The strip casting process is expected to be applied to ferritic stainless steels and high-alloy steels for which rapid solidification will prove particularly beneficial.

3.2 Hot rolling

Hot rolling is an important process that governs the mechanical properties, surface quality, and cold rollability of stainless steels. Hot rolling mills for stainless steels are available in two types. Hot strip mills are used by producers of stainless as well as carbon steels. Stainless steel makers mainly use Steckel mills. Four-high mills are chiefly employed for rolling plates, while four-high continuous mills are used for rolling wire rods. In recent years, block mills capable of precision rolling have been adopted at an increasing rate. The hot rolling of strip and plates is principally described below.

Among the hot rolling technology developments and improvements accomplished to data are: improvement in mechanical properties and surface quality by integrated controlled rolling from heating to coiling; better surface quality by upgrading roll materials and use of rolling lubricants; superior gage accuracy by adopting automatic gage control (AGC); crown and shape control by shifting work rolls in six-high mills and by adopting pair cross mills; higher quality because of the introduction of a coil box; and manufacture of thin-gage and heavy-weight coils. Labor and process step savings, and quality advances have been achieved in this way. Future issues of particular importance are the installation of strip casters and the application of the continuously rolling welded slabs process to stainless steels, already employed in the carbon steel field. Such technology will enhance efficiency and achieve superior head and tail end size and shape.

The controlled rolling technology that eliminates solution heat treatment by the thermomechanical control process (TMCP) and the technology of producing heavy-gage plates from continuously cast slabs by controlling rolling operations were developed and applied for plate rolling. For wire rod rolling, block mills are applied to boost rolling speed. Precision products with dimensional tolerances of ±0.1 mm are manufactured by three-roll mills and sizing mills after block mills. The direct solution treatment (DST) technology that eliminates annealing by controlled rolling and cooling is also adopted.

3.3 Cold rolling

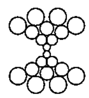
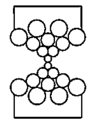
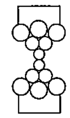
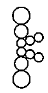
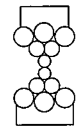
Cold-rolled stainless steels were traditionally produced by what is called the stainless steel process using Sendzimir mills, but recently, a tandem process that makes use of the carbon steel process has been developed. The cold rolling of stainless steels is described here, centering on the former process. Hot coils were historically continuously annealed for austenitic stainless steels, but SUS 430 was box annealed on a batch basis. In 1982, Nippon Steel developed and commercialized continuous annealing technology that involves adding aluminum and shifting the austenite transformation range to a higher-temperature side[10]. The technology of incorporating the hot coil annealing function into the hot rolling process by controlled hot rolling[11] and the technology of directly connecting annealing, pickling and cold rolling by installing a tandem cold mill at the delivery end of the annealing and pickling line have been practically applied recently[12].

The cold rolling of stainless steels encounters higher deformation resistance than that of carbon steels and hence uses cluster mills with work rolls of smaller diameter, as listed in **Table 3**[13].

Besides these stainless steel cold rolling mills, a carbon steel tandem mill process using large-diameter rolls is also commercially exploited. This process is highly productive and is used for cold rolling heat-resistant steels and stainless steels, mainly for automobile exhaust system components.

High-accuracy automatic gage control, automatic shape control, and various other control techniques are applied in stainless steel cold rolling. In addition to quality improvements concerning thickness accuracy and shape accuracy, high-speed rolling in excess of 800 mm/min is accomplished, as shown in **Fig. 6**[14]. Along with the progress of cold rolling mills, tribological research is carried out to increase rolling speed and enhancing the surface luster of rolled products. These results will be incorporated to

Table 3 Types and characteristics of recent stainless steel cold rolling mills

Type		Z-mill	KST mill	KT mill	UC mill	CR mill
Manufacturer		Sendzimir (Hitachi)	Kobe Steel	Kobe Steel	Hitachi	Mitsubishi Heavy Industries
Roll arrangement						
Abbreviation		Sendzimir mill	Kobelco Sandvik Twenty-high mill	Kobelco Twelve-high mill	Universal Crown control mill	Cluster-type Rolling mill
Characteristics	Shape control function	• Divided backup roll bender • First intermediate roll lateral shift	• Divided backup roll bender • First intermediate roll lateral shift	• Divided backup roll bender • First intermediate roll lateral shift	• Intermediate roll shift • Intermediate roll bender • Work roll bender	• Divided backup roll crown adjustment • Intermediate roll bender • Work roll bender
Characteristics	Gage control function	• Hydraulically drived screwdown and eccentric mechanism	• Wedge-type hydraulic screwdown • Electrically drived screwdown rolling	• Wedge-type hydraulic screwdown • Electrically drived screwdown rolling	• Hydraulic screwdown cylinder • Hydraulically drived screwdown rolling	• Hydraulic screwdown cylinder • Hydraulically drived screwdown rolling
Characteristics	Housing structure	• One-piece housing	• Four-post separate housing	• Four-post separate housing	• Separate housing	• Separate housing
Characteristics	Work roll: Diameter reduction	• Extreme diameter reduction possible	• Extreme diameter reduction possible	• Diameter reduction possible	—	• Diameter reduction possible
Characteristics	Work roll: Chock	No	No	No	No	No
Characteristics	Roll drive	Top and bottom first intermediate rolls	Top and bottom first intermediate rolls	Top and bottom intermediate rolls	Top and bottom intermediate rolls	Top and bottom intermediate rolls

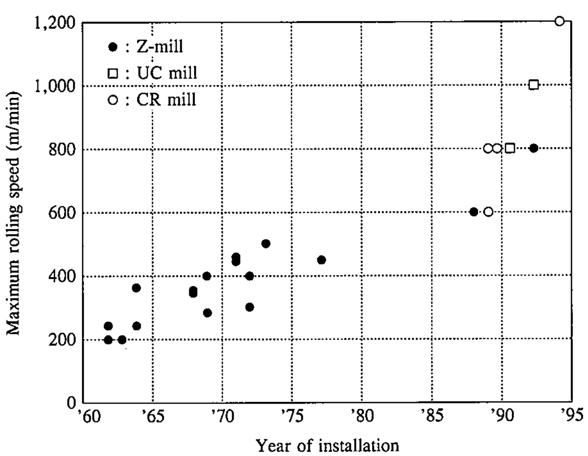


Fig. 6 Increase in rolling speed of reversing stainless steel cold rolling mills

achieve still higher efficiency and quality and to expand the applicable scope of the tandem process.

The annealing and pickling of cold-rolled sheet and strip has increased in speed and efficiency, and has made progress in terms of quality control. A typical example of a recent cold-rolled stainless steel continuous annealing and pickling (CAP) line is shown in **Fig. 7**[15]. This CAP line runs at a high speed of 100 m/min and adopts the combination of neutral salt electrolysis and alkaline electrolysis in place of molten salt treatment as the pickling pretreatment. The annealing furnace is of the energy-saving type with such a long preheating zone that the efficiency of preheating with waste gas is enhanced. Strip thickness and width are measured for quality control purposes, surface flaw detectors are installed, and surface luster, surface roughness and grain size are measured in-line. Some other lines have the number of finishing process steps reduced by the in-line installation of a skinpass mill, tension leveler and side trimmer at the delivery end of the line. Direct-firing burners are used for rapid heating, and air cushion bearing, which float the strip by air are installed in the line. As an antipollution measure, spent nitric-hydrofluoric acid is recovered by the ion exchange membrane diffusion osmosis method or by the electrolytic separation method. New pickling solutions are being extensively studied to reduce nitrogen oxide emissions.

Technological developments for bright annealing are similar to those for pickling and annealing. Electrolytic alkaline cleaning is applied to degreasing, and muffle furnaces are adopted on large lines.

The finishing process has strip shape and productivity improved by the in-line installation of a skinpass mill on the CAP line and the adoption of a six-high skinpass mill as already described. The introduction of automatic coil transfer equipment and the automation of product packaging are in progress.

4. Increase in Functionality of Stainless Steels

The recent changes in the types of stainless steels specified in the Japanese Industrial Standards (JIS) are listed in **Table 4** as one indicator of the increases in the functions required of stainless steels and in the number of new technologies and grades developed to meet these requirements. The numbers by property of proprietary stainless steel grades produced by specific manufacturers are given in **Table 5**. The JIS stainless steels have greatly grown in numbers in the past 20 years. Points of particular interest are that many grades with high corrosion resistance or strength

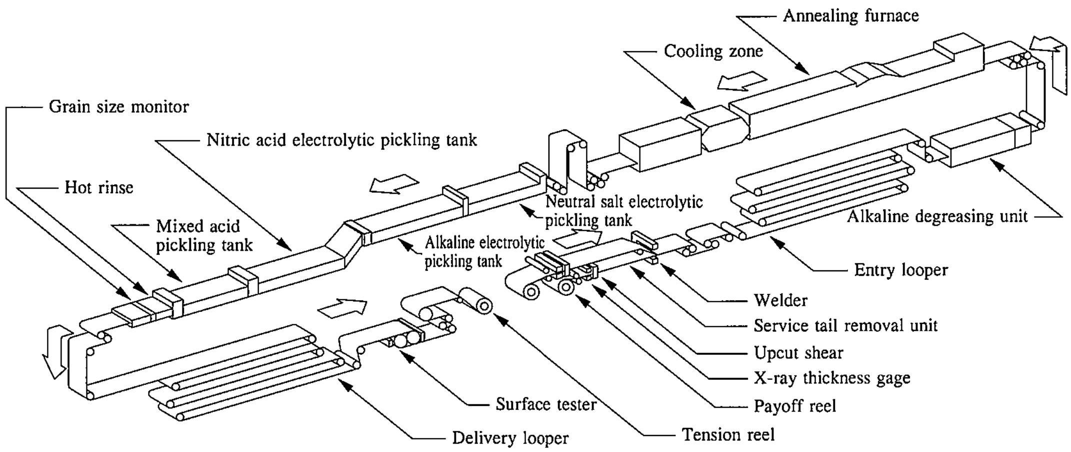


Fig. 7 Configuration of recent CAP line

Table 4 Main changes in JIS stainless steels

Division \ JIS revision year		1972	1981	1991
Number of types as classified by microstructure	Martensitic	12	14	16
	Ferritic	5	11	12
	Austenitic	23	39	49
	Duplex	1	1	3
	Precipitation-hardening	3	3	3
	Total	44	68	83
New types as classified by main property	High corrosion resistance	—	9	18
	High formability	—	4	7
	High strength or hardness	—	9	11
	High machinability, etc.	—	2	3

Note: Properties as described in applicable JIS

Table 5 Proprietary stainless steels produced by manufacturers in Japan

		Nippon Steel	Nisshin Steel	Kawasaki Steel	Sumitomo Metal	Nippon Metal	Nippon Yakin
	Corrosion resistance	7	2	3	9	7	16
	Formability	1	6	5	5	5	6
	Machinability	0	0	0	4	3	0
	Strength	6	8	3	6	8	5
	Heat resistance	2	6	1	6	3	4
	Others	0	2	0	0	0	0
Austenitic		16	24	12	30	26	31
	Corrosion resistance	9	9	19	11	9	7
	Formability	2	3	4	0	2	1
	Heat resistance	7	8	9	10	5	1
	Weldability	2	3	3	0	1	4
Ferritic		20	23	35	21	17	13
Martensitic		2	4	3	0	2	0
Duplex		1	2	1	11	4	3

Note: Subtypes are also individually counted.

have been added and that many proprietary corrosion-resistant grades are produced by the stainless steelmakers.

4.1 High corrosion-resistant stainless steels

It is well-known that the first stainless steel developed and commercialized was a 13% chromium martensitic stainless steel. The martensitic stainless steels were followed by austenitic, ferritic, and duplex stainless steels in that order. The progress of stainless steelmaking and hot rolling technologies has enabled manufacturers to develop and launch new grades with high corrosion resistance one after another.

The latest high corrosion-resistant stainless steels may be divided into two groups. One group comprises the so-called super stainless steels. A typical one is Nippon Steel's YUS 270 (20Cr-18Ni-6Mo-N), featuring corrosion resistance comparable to that of titanium. YUS 270 is high in chromium and molybdenum, makes effective use of nitrogen as an element for improving corrosion resistance, and is classified as a high-strength steel as well. Although an austenitic alloy, YUS 270 falls between austenitic and ferritic stainless steels as far as its thermal expansion coefficient is concerned. It is used in seawater desalination plants and chemical plants and is finding applications as a wall and roofing material resembling bare stainless steel in coastal and salt damage-prone areas such as Okinawa. The ferritic stainless steel SUS 447 J1 (30Cr-2Mo) also belongs to the super stainless steel group.

The other group covers the high-purity ferritic stainless steels. Corrosion resistance and formability are improved by adding chromium and molybdenum and by lowering the levels of the interstitial elements carbon and nitrogen while making the most of the refining processes described above. Controlled hot rolling made it possible to produce the high-purity ferritic stainless steels industrially and commercially. Typical examples are Nippon Steel's YUS 220M (22Cr-1.5Mo-Ti-Nb), and YUS 190 and YUS 190L (19Cr-2Mo). High-purity stainless steels with different chromium and molybdenum levels are produced in series by other Japanese stainless steelmakers as well. Nippon Steel's high-purity ferritic stainless steels are shown in relation to their pitting index (PI) in **Fig. 8**. In addition, YUS 260 (20Cr-15Ni-3Mo-Cu-N), YUS 110M (18Cr-12Ni-2Si-Mo-Cu), and YUS 27A-M (17Cr-7Ni-2Cu-2Si) were recently developed as stainless steels with high corrosion resistance.

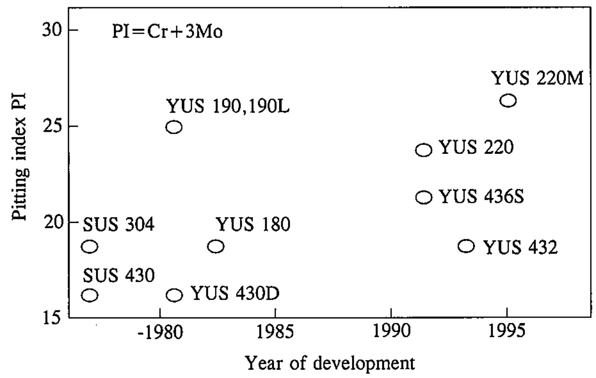


Fig. 8 Nippon Steel's main high-purity ferritic stainless steels

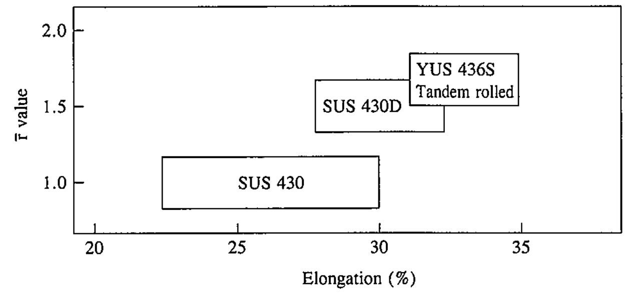


Fig. 9 Formability of high-purity ferritic stainless steels

Corrosion resistance is improved by adding titanium and niobium in combination as well as by adding chromium and molybdenum and lowering the carbon content. The combined addition of titanium and niobium renders nonmetallic inclusions more difficult to dissolve as sites to initiate corrosion and concentrates titanium as oxide in the passive film, thereby improving corrosion resistance. Nippon Steel has long utilized this technology for YUS 190 and YUS 220M, for example. Other stainless steelmakers have recently begun research in this area. Utsunomiya et al. reported that corrosion resistance can be improved by the combined addition of titanium, niobium, and aluminum[16]. Yamagishi et al. found that sulfur, traditionally regarded as a harmful element, improves the intergranular corrosion resistance of low-chromium stainless steels in the same way as nitrogen is found to be effective in improving the corrosion resistance of austenitic stainless steels[17]. Research on raising corrosion resistance is thought to make further progress in terms of inclusion control and protective surface films.

4.2 Highly-formable stainless steels

Stainless steels are often said to be difficult to form. Ferritic stainless steels are inferior in ductility to mild steel. Austenitic stainless steels are high in strength and have a high coefficient of thermal expansion in forming operations involving welding heat. Ferritic stainless steels are discussed here in relation to formability. As noted in Section 4.1, lower carbon and nitrogen contents have significantly improved formability in general and drawability in particular. The formability indexes of recent high-purity ferritic stainless steels are shown in **Fig. 9**. The $\bar{r}$ value, which was about 1.0 for SUS 430, is improved to about 1.6 for SUS 430D. Elongation in excess of 30% can be stably obtained. The $\bar{r}$ value of the tandem-rolled YUS 436S is dramatically improved, partly under the influence of rolling with large-diameter rolls. Unlike SUS 304, consequently, these new ferritic stainless steels can be extra-deep drawn if drawing conditions are appropriate. Ultrahigh-purity Fe-Cr alloys are improved further in these properties, and a 18% chromium steel is reported to achieve an elongation of more than 36%[18].

As stainless steel wire rods have increased in production, they have encountered increasing demand for higher productivity and lower cost. As a result, their fabrication method is shifting from machining to forging[19]. New stainless steels with cold forgeabilty better than that of the conventional cold-forging stainless steel SUS XM7 are widely employed to meet severe cold forging conditions. Free-machining steels and critical compression ratio-improved steels, each with additions of lead and selenium as well as sulfur, have also been developed.

Lubricated stainless steel sheets have recently come into the spotlight as materials to offset the lack of formability of stainless steels. Coated with a lubricant-containing organic film, this type of product can be formed without lubricating oil or protective film and is expected to have many applications as a material for improving the working environment and lowering manufacturing costs. Nippon Steel developed and commercialized such an organic film, named "Guardcoat," jointly with Tokai Steel Works and has applied it to stainless steels as well.

4.3 Artistic stainless steels

Highly corrosion-resistant stainless steels are mainly available in two finishes: No. 2B finish produced by annealing and pickling and BA finish with high luster in the as-rolled condition retained by annealing in a controlled-atmosphere furnace. They are extensively used in kitchenware, bathtubs, and interior and exterior building materials, among other applications, after polishing (to No. 3, No. 4, No. 7, or mirrorlike finish), embossing, dull finishing, etching or coloring (painting, chemical coloring like Incocolor, ion plating, or dry coating).

Among the new types of stainless steel products that have recently come into use to meet diversified and differentiated needs are: Elliosheet stainless steel sheets with printed patterns; tunnel interior stainless steel sheets with high-hardness coatings and high corrosion-resistant paints for beautifying tunnels; special prepainted stainless steel sheets such as those coated with antimycotic and antibacterial paints; and stainless steel sheets coated with aluminum, zinc or other metals to emphasize the color of coating metals not obtainable with paints.

The aluminum coating of aluminum-coated stainless steels has a sacrificial protection effect. In addition, the diffusion of chromium from the steel into the aluminum coating increases the corrosion resistance of the steel. In this way, the aluminum coating contributes to the overall improvement in corrosion resistance of aluminum-coated stainless steels. The scratches from polishing performed as preparation for painting were recognized as an artistic finish, and stainless steels with such as-polished finish were commercialized as vibration-polished products. As evident from this example, new artistically attractive stainless steel products will be developed if ideas are matched with appropriate technology and cost performance.

4.4 Other functional stainless steels

Stainless steels are available in many types to meet many properties and applications. Several examples representing the results of technological progress in stainless steel production follow.

4.4.1 High-strength and high-hardness stainless steels

A modification of SUS 301L developed for railroad cars is applied as a construction material for applications where high strength and hardness are required, such as automobile gaskets and press-plates. In the civil engineering and building sector, martensitic stainless steels with improved corrosion resistance, such as YUS 550 (13Cr-2Ni-2Mo), have been developed and applied for punching concrete without drilling. Based on SUS 316 and having an optimum nitrogen addition, SUS 316FR (16Cr-12Ni-2Mo-0.09N) has been developed for fast breeder reactors and is expected to find use in other applications where elevated-temperature strength and creep strength are demanded.

Ferritic stainless steels with elevated-temperature strength conferred by niobium additions have been developed and are used in automobile exhaust manifolds, among other things. YUS 180H (19Cr-0.8Nb) and YUS 340-MS (14Cr-0.5Mo-0.3Nb-Ti) are such examples.

4.4.2 Nonmagnetic stainless steels

Austenitic stainless steels are usually nonmagnetic in the solution-annealed condition. Depending on the stability of austenite, cold working produces martensite transformation and causes the austenitic stainless steel to exhibit magnetism. YUS 130S (18Cr-6Ni-10Mn-0.3N), which that retains a low magnetic permeability of about 0.01 or less, in the worked condition, was developed for applications where cold workability is required. Magnetically soft ferritic stainless steels have been developed one after another by adding aluminum.

4.4.3 Heat-resistant and oxidation-resistant stainless steels

High-chromium stainless steel is heat and oxidation resistant, and is used in combustion equipment and other applications where heat resistance and oxidation resistance are required. The addition of aluminum and silicon, for example, further improves the heat resistance and oxidation resistance of high-chromium stainless steel. YUS 701 (25Cr-13Ni-2Si-Mo-N) and YUS 731 (19Cr-13Ni-3Si-0.7Cu) were developed as stainless steels resistant to both heat and oxidation. Such austenitic stainless steels have the drawback of expanding at high temperatures, depending on applications. Nippon Steel has developed and mass-produced HOM125 (15Cr-4Al) and YUS 405Si (12Cr-2Si-Al) as ferritic stainless steels excellent in this respect. YUS 205-M1 (20Cr-5Al-REM) with increased chromium and aluminum content and rare earth element additions was developed for automotive catalytic converters that require heat resistance and oxidation resistance at temperatures up to about 950°C.

Stainless steel coated with heat-resistant resin is commercially used in table-top cookers and other applications where heat resistance to about 260°C is required. Microwave oven inner housings, for example, call for pre-coated materials (PCM) with heat resistance to about 550 to 600°C. Stainless steels with higher heat resistance as well as improved formability are subjects of development for such applications.

Table 6 Recent examples of stainless steel substitution

Market	Application or part	Material			Purpose of stainless steel substitution	Period					
		Before change	After change	Consumption (kg/unit)		-'89	'90	'91	'92	'93	'94
Automobiles	• Mufflers	Aluminum-coated carbon steel	SUS 436L YUS 432	8	Longer product life		⇒			⇒	
	• Exhaust manifolds	Casting	SUS 430J1L YUS 450-MS	4	Life extension and weight reduction	⇒				⇒	
	• Catalytic converters	Ceramic	YUS 205-M1	1	Weight reduction and efficiency improvement			⇒			
	• Metal gaskets (one-piece construction)	Asbestos	SUS 301	0.4	Safety	---	---	⇒			
Electrical appliances	• Clothes baskets	Plastic	SUS 430LX	3-6	Spin-dry efficiency improvement	---	---	---	⇒		
	• Clothes dryers	Galvanized carbon steel	SUS 430LX, etc.	4	Product differentiation						⇒
	• Induction heating rice cooker jars	Aluminum, etc.	Stainless steel-aluminum clad material	2	Rice cooking efficiency improvement		⇒				
Buildings	• Roofing	Prepainted carbon steel	YUS 220M, etc. YUS 270	3-10	Corrosion resistance improvement	⇒					
	• Structural members	Carbon steel	SUS 304		Corrosion resistance and artistic improvement			⇒			
	• Tunnel interior sheets	Asbestos, tiles	22 Cr stainless steel + painting	6kg/m²	Safety			⇒			
Civil engineering	• Dams and weirs	Carbon steel	SUS 304	2,000 t/dam	Maintenance-free operation (elimination of painting)	---	---	---	---	⇒	
	• Colored material for concrete pipe	Carbon steel + painting	SUS 304N1,SUS 316		Longer product life	---	⇒				
	• Water pipe bridges	Carbon steel + painting	SUS 316,SUS 329J4L		Maintenance-free operation	---	---	---	⇒		
	• Prestressed concrete reinforcement material	Carbon steel	SUS 304		Longer product life	---	⇒				
Industrial machinery, etc.	• Chimney linings	Refractory	YUS 260		Maintenance-free operation	⇒					
	• Cable protection tubes	Carbon steel + painting	SUS 304		Longer product life	⇒					

4.4.4 Composite steel sheets and plates

Various clad stainless steel sheets and plates have been traditionally used as materials combining the functions of stainless steel with those of another metal. Other composite steel sheets and plates to which stainless steels are applied include vibration-damping stainless steels and resin-laminated stainless steels. Nickel-coated, copper-coated, and solder-coated stainless steels are available as flat-rolled products with good solderability.

The main examples where stainless steels that were recently substituted for other materials by taking advantage of the functions listed in **Table 6**.

5. Conclusions

Stainless steel manufacturing technologies and major stainless steel products were summarized. Amid concerns about the deterioration of the global environment and the changes of adaptating to aging societies, long-lasting and recyclable stainless steels are being extensively studied as substitutes for carbon steels that must be painted or coated and as future materials, for example, for clean energy production facilities and bridges that will last for 300 years. The issue of life cycle assessment (LCA) is expected to promote the use of stainless steels in many new applications. To realize this objective, stainless steel manufacturers will have to work together with stainless steel users to develop new stainless steels that costless, have increased functions, have greater uniformity in quality.

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