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Special Issue on Stainless Steels

Manufacturing Process and Properties of Stainless Steels

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Manufacturing Process and Properties of Stainless Steels*


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1 Introduction

Mass production of stainless steels at Kawasaki Steel was started in 1961 with a construction of a Sendzimir mill for wide strip rolling as a momentum. The development of new steel grades with their properties improved on the conventional stainless steels such as SUS 430 (AISI type 430) and SUS 304 (AISI type 304) began with an introduction of VOD equipment (ELO-VAC furnace) in 1971, and virtually reached its apex with a subsequent development of the SS-VOD process. At that time, main emphasis was placed on the saving of nickel resources, and the making of ferritic stainless steels with their properties closest possible to the excellent properties of austenitic stainless steels was considered to be a way of producing higher-grade stainless steels at low cost. Ultra-low cabon and nitrogen steels made by the SS-VOD process have been used mainly for this purpose. This paper presents an outline of the manufacturing process and properties of stainless steels, especially those developed by Kawasaki Steel.

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2 Manufacturing Process

2.1 Steelmaking Process

The manufacturing process of stainless steels at Kawasaki Steel is shown in **Fig. 1** by the shapes of finished products. The company's stainless steels are produced by making the most of the features of an integrated iron and steel manufacturer. Especially, the steelmaking process has undergone a great change since the introduction of converters which opened the way of using molten pig iron as main raw material instead of scrap conventionally used in electric furnaces. In the case of ferritic and martensitic stainless steels, molten pig iron and ferrochromium are refined in the K-BOP vessel [1] (top- and bottom-blown converter that serves also to produce ordinary steels), the world's first combined-blown converter. For austenitic stainless steels, scrap, ferrochromium and ferronickel are melted in the UHP electric furnace beforehand and this molten steel is refined in the above-mentioned K-BOP vessel. Then, both are degassed in the RH vacuum degasser and continuously cast [2,3] into slabs. This process is a routine steel refining method adopted at the company to produce

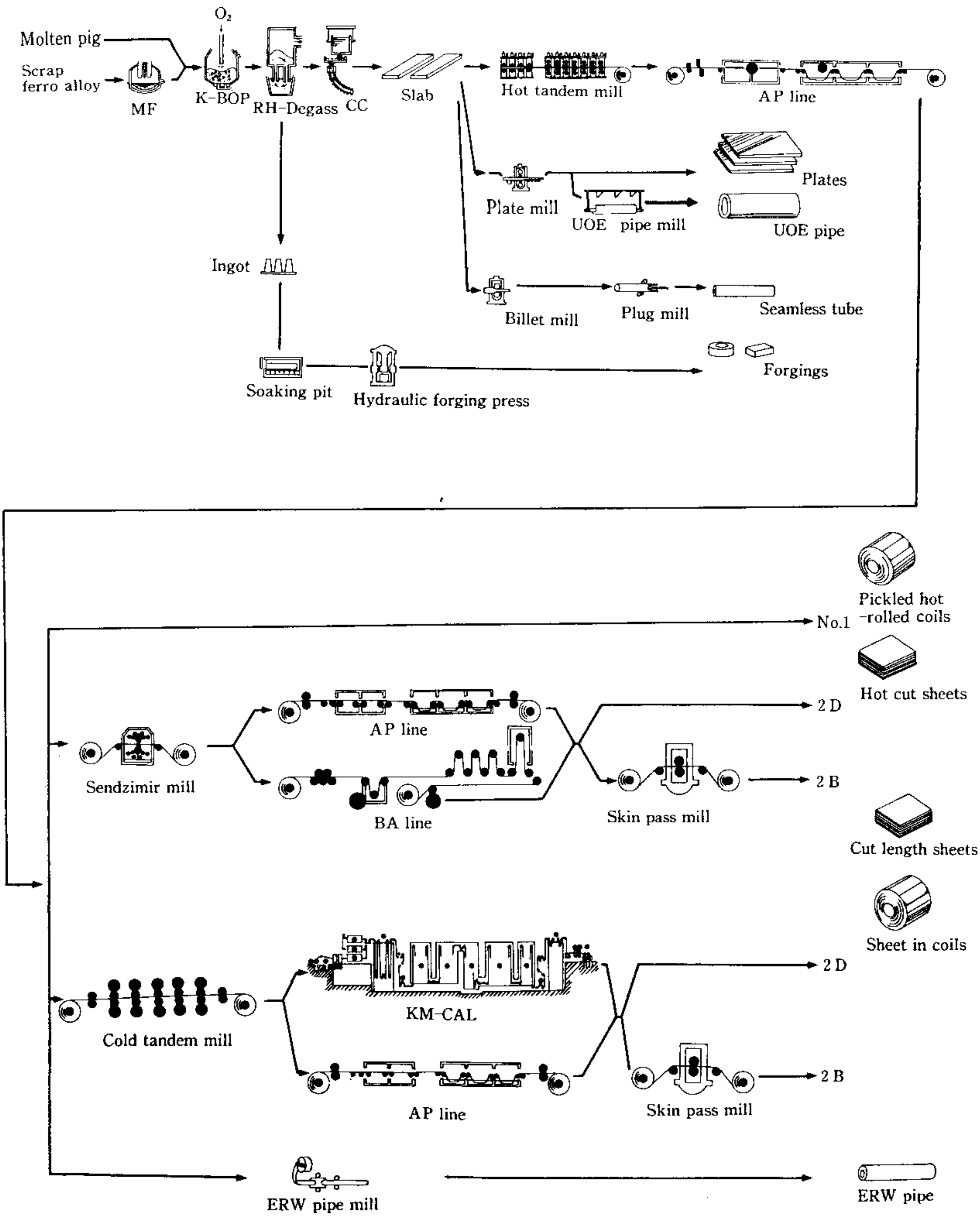


Fig. 1 Manufacturing process of stainless steels in Kawasaki Steel

commercial-grade stainless steels. As will be described later, the refining by the K-BOP process is insufficient for producing super ferritic stainless steels with ultralow carbon and nitrogen contents, requiring decarburization and denitrization using the SS-VOD equipment[4], the company's own improvement over the VOD equipment. The concentration of carbon and nitrogen attainable with this equipment is currently 20 and 50 ppm, respectively, in a 30% Cr stainless steel.

Table 1 List of stainless steels developed by Kawasaki Steel (%)

	Referred designation of JIS	Designation of developed steels	C	Si	Mn	Cr	Ni	Mo	Cu	others	Improved properties
Ferritic	SUS 410	R 410 L	≤0.030	≤1.00	≤1.00	11.50~13.50	—	—	—	—	Weldability, oxidation resistance
Ferritic	SUH 409	R 409 SR	≤0.015	1.00~2.50	≤1.00	10.00~12.00	—	—	—	Ti≤0.50	Weldability, oxidation resistance
Ferritic	SUS 430	R 430 LT(N)	≤0.030	≤0.75	≤1.00	16.00~18.00	—	—	—	Ti(Nb) 0.10~1.0	Drawability, Weldability, corrosion & oxidation resistance
Ferritic	SUS 430	R 430 CuN	≤0.030	≤1.00	≤1.00	17.50~19.50	—	—	0.40~0.70	N≤0.030 Nb≥10(C+N)	Drawability, corrosion resistance
Ferritic	SUS 430	R 430 LNM	≤0.030	≤1.00	≤1.00	16.0~19.0	—	0.40~0.80	—	N≤0.030 Nb 0.20~0.70	Corrosion resistance
Ferritic	SUS 430	ALT-15	≤0.015	≤0.50	≤0.50	14.50~15.50	—	—	—	Al 2.8~3.6 Ti 0.10~1.00 REM 0.1~0.6	Oxidation resistance
Ferritic	SUS 430	ALT-18	≤0.012	≤0.09	0.25~0.50	17.50~18.50	—	—	—	Al 2.8~3.6	Oxidation resistance
Ferritic	SUS 434	R 434 LT-1, LN-1	≤0.020	≤1.00	≤1.00	16.00~19.00	—	0.75~1.25	—	Ti(Nb) 10(C+N)~0.80	Corrosion resistance, weldability, workability
Ferritic	SUS 434	R 434 LT-2, LN-2	≤0.020	≤1.00	≤1.00	17.50~19.50	—	1.75~2.25	—	Ti(Nb) 15(C+N)~0.80	Corrosion resistance, weldability, workability
Ferritic		SHOMAC RIVER 26-1*1)	≤0.010	≤0.40	≤0.40	25.00~27.50	—	0.75~1.50	—	N≤0.015	Corrosion resistance
Ferritic		SHOMAC RIVER 26-4*1)	≤0.010	≤0.40	≤0.40	25.00~27.50	—	3.75~4.50	—	N≤0.015	Corrosion resistance
Ferritic		SHOMAC 30-2*1)	≤0.010	≤0.40	≤0.40	28.50~32.00	—	1.50~2.50	—	N≤0.015	Corrosion resistance
Martensitic	SUS 410	R 410 DH	≤0.020	≤0.50	1.00~2.50	10.75~13.50	—	—	≤1.00	—	Weldability
Martensitic	SUS 410	R 410 DB	≤0.090	≤0.50	1.00~2.50	10.00~14.50	—	—	—	C+N: 0.04~0.10	Wear & corrosion resistance, easy heat treatment
Martensitic		HCS 16*2)	0.25~0.40	<1.00	<1.00	15.00~17.00	—	—	—	—	Corrosion resistance
Austenitic	SUS 301	R 301 L	≤0.03	≤1.00	≤2.00	16.00~18.00	6.00~8.00	—	—	—	Corrosion resistance
Austenitic	SUS 301	R 301 R*3,4)	0.12	0.90	1.03	16.30	6.25	—	—	—	Spring properties
Austenitic	SUS 304	R 304 UD	≤0.15	≤1.00	≤2.00	13.00~15.00	6.00~8.00	≤1.00	1.00~3.00	—	Drawability
Austenitic	SUS 304	R 304 MN*3)	0.034	0.15	8.6	15.5	2.5	—	2.5	—	Drawability
Austenitic	SUS 304	R 304 Cu	≤0.080	≤1.00	≤2.00	18.00~20.00	8.00~10.50	—	1.0~2.0	—	Stress corrosion resistance
Austenitic	SUS 304	R 304 CuL	≤0.030	≤1.00	≤2.00	18.00~20.00	9.00~13.00	—	1.0~2.0	—	Stress corrosion resistance
Austenitic	SUS 316	R 316 LNX*3)	0.024	0.52	1.00	17.38	11.98	—	—	N 0.15 V 1.00	Cryogenic properties
Austenitic		RXM 15	≤0.080	3.00~5.00	2.00	17.00~23.00	11.50~15.00	—	—	REM 0.05~0.20	Oxidation resistance

Notes *1 Developed in co-operation with Showa Denko K.K.
*2 Developed in co-operation with Honda R & D Co., Ltd.
*3 Typical chemical contents
*4 Developed in co-operation with Nippon Kinzoku Co., Ltd.

2.2 Rolling Process

Main product types to be taken up in this paragraph will be sheets and strip. The process up to and including hot rolling is performed at Chiba Works as part of integrated production. Hot rolling is performed on a hot tandem mill. Crown control[5] by the work-roll shifting is conducted to reduce gage variations of products, and at the same time, emphasis is laid on large unit weights and small thicknesses to raise the efficiency in the cold rolling process. The annealing and pickling of hot coils are carried out in the KM-AP line provided with waste recovery equipment[6] (multiple-purpose type capable of passing both hot and cold coils up to 5 feet in width and up to 8 mm in thickness). At Chiba Works, stainless steel plates are produced from continuously cast slabs using a plate mill and large-diameter steel pipe is produced from these plates. In addition, the production of clad plates by the enshrouding casting method is carried out, and clad strip used as the materials for clad sheets is also produced. The materials for seamless stainless steel pipe[7] made at Chita Works and stainless steel forgings[8] produced at Mizushima Works are supplied from Chiba Works.

The cold rolling process is mainly performed at Hanshin Works. The principal mill of this cold rolling line is a Sendzimir mill. Stainless steels are required to possess good apperances, such as beautiful surfaces and good flatness, in addition to their unique quality requirements. To meet these requirements, a high-tension skinpass mill[9] and an automatic finishing line[10] are provided and production based on high technologies is carried out. Furthermore, the cold rolling line is provided with buffing equipment, flow coater, protective film applicator, coating equipment, etc. to meet diversifying applications such as hair line, clear coating, and coated color stainless steel.

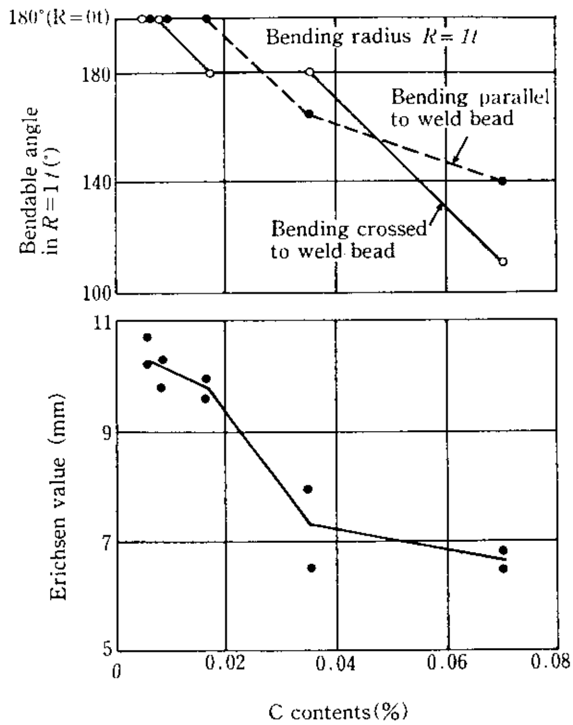
The foregoing is the manufacturing process of stainless steels more or less in the conventional manner. At Chiba Works, however, another manufacturing process has recently been adopted for limited applications; that is, high-efficiency cold rolling is perfomed in the same line as with carbon steels, i.e., in a cold tandem mill in place of a Sendzimir mill and cold-rolled coils are finished in the KM-CAL (Kawasaki Steel multipurpose continuous annealing line) or the conventional annealing and pickling line.

Thus the company's stainless steels are manufactured for wide applications by making the best use of the features of an integrated steel manufacturer.

3 Product Properties

3.1 Ferritic Stainless Steels

The basic steel grade of ferritic stainless steels is SUS 430. This steel grade has long been used in durable consumable goods as a material less expensive than SUS 304. SUS 430 has been mass-produced together with austenitic stainless steels such as SUS 304, with its quality established to be very stable. However, because of its high carbon content, SUS 430 develops the austenite phase at a high temperature and martensitic transformation occurs during cooling. As a result, the heat-affected zone (HAZ) becomes embrittled or intergranular corrosion takes place. This is the drawback of SUS 430. To improve this point, it is necessary to lower the carbon content (nitrogen content). By the conventional steel making techniques using electric furnaces, however, the decarburization of steel was limited to only about 0.02%. Breakthrough in this problem was made by the ladle refining process that has recently made a rapid progress, and new products (**Table 1**) have been developed one after another by the company's SS-VOD process,[4] one of the most excellent ladle refining processes.



TIG Welding
Welding velocity: 30 cm/min
Electric current: 65 A
Ar in torch side: 15 l/min
Ar in rear side: 7 l/min

Fig. 2 Effect of C contents on bendability of TIG weldment and Erichsen value in 12% Cr stainless steels (1.2 mm thickness)

Decarburization of chromium stainless steel not only prevents the martensite formation after rapid cooling of SUS430 ferritic stainless steel, but also transforms the martensitic stainless steel such as SUS410 into ferritic type. As a matter of fact, therefore, weldability has been greatly improved in these steels. In addition, improvements have been made also in oxidation resistance, corrosion resistance, and press formability.

Figure 2[11] shows the effect of the carbon content on the bendability and Erichsen value of a TIG welded joint of 12% Cr stainless steel sheets (SUS 410). **Table 2**[12] shows the results of the bending test on a welded joint of a conventional 17% Cr steel with a carbon content of 0.06% (SUS 430) and a 17% Cr steel decarbulized to 0.015% C and added titanium to stabilize the remained carbide as TiC (**R430LT**).

Figure 3[11] shows the relationship between an increase in weight due to oxidation and the carbon content when the 12% Cr steel is repeatedly oxidized in the air at 900°C. As is apparent from the figure, the increase in weight decreases substantially with decreasing carbon content. **R 410 L** and **R 410 UL** are inexpensive 12% Cr stainless steels developed based on these results and the above-mentioned improvement in weldability, and they currently used in heat resistant applications, such as automobile exhuast gas pipe.

R 409 SR is used in heat-resistant applications. This grade was developed by lowering the carbon content of the heat-resistant steel AISI 409 that has so far been used in exhaust pipe at U.S. automobile manufacturers and by adding silicon to enrich the SiO_2 in scale from the standpoint of oxidation resistance.[12] This steel has the most excellent oxidation resistance at temperatures up to 900°C among the stainless steels currently in use (**Fig. 4**). The applications of R 409 SR include the combustion chamber of an oil-stove.

The foregoing is mainly related to the effects of decreased carbon contents of 12% Cr stainless steels. About ten years ago, when the 1976 automobile emission control was enforced, steels that can withstand serv-

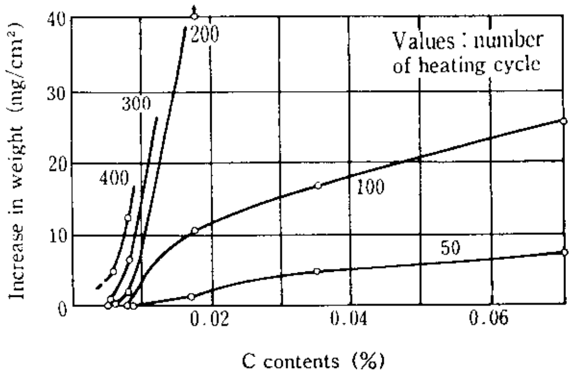


Fig. 3 Effect of C content on weight change of 12% Cr steel in cyclic heating in air at 900°C (1 h heating, 5 min cooling)

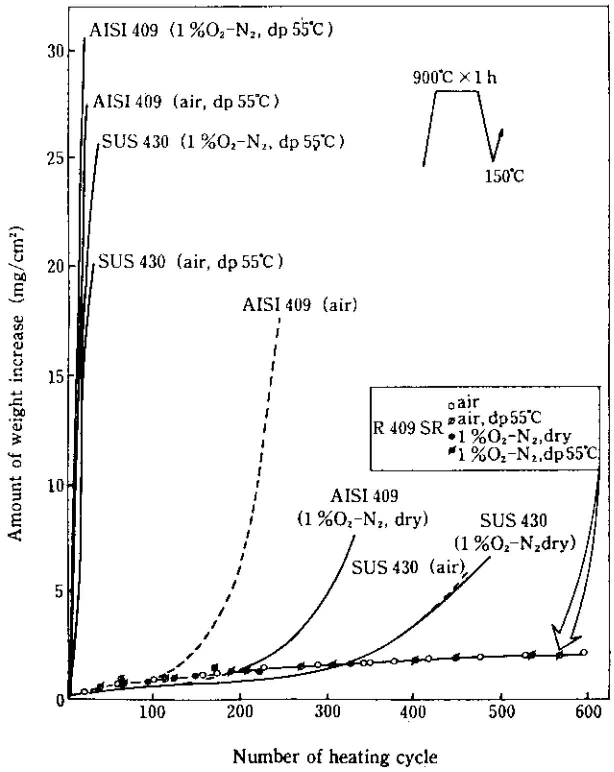


Fig. 4 Oxidation resistance in wet atmosphere

Table 2 Welding conditions and bending test results

Welding method	Welding condition							Max. angle of bending* (°)	
	Current (A)	Voltage (V)	Electrode force (kg)	Duration (cycle)	Velocity (cm/min)	Welding joint	Remarks	R 430 LT	SUS 430
Spot weld	8 000	—	400	5	—	lap	electrode dia. 5.5 mmϕ	180	110, 180
	9 300	—	400	5	—	lap		180	110, 180
	10 500	—	400	5	—	lap		180	100, 105
TIG	70	20	—	—	30	butt	Ar flow 10 l/min	180	30
	80	20	—	—	30	butt		180	20
	90	20	—	—	30	butt		180	15

* R=2 t for spot weldment and R=0 t for TIG weldment with 1.2 mm thick stainless steel sheets

ices at more than 1 000°C were developed for use in exhaust gas cleanup equipment, especially thermal reactors. **ALT-15** and **ALT-18** were developed at that time.[13] In these two steels, Al_2O_3-rich scale is formed by adding aluminum to give good oxidation resistance to the surface of a low-carbon 15% Cr steel and a low-carbon 17% Cr steel, respectively, and the adhesion of scale to the steel surface is ensured by adding REM. These two steels were not put into practical use in automobile exhaust gas cleanup systems, because the gas cleanup systems of thermal reactor type were replaced with those of converter type soon after. However, new applications such as an oil-stove combustion chamber and a radiator are being examined for these steels.

The 17% Cr stainless steels **R 430 LT(N)**, **R 430 CuN** and **R 430 LNM** were developed mainly to improve corrosion resistance. R 430 LT[14,15] is the oldest of all ferritic stainless steels developed by Kawasaki Steel. In this steel, solute carbon is fixed as TiC by lowering the carbon content of SUS 430 and adding titanium, whereby intergranular-corrosion sensitization is eliminated by preventing the precipitation of chromium carbides at the grain boundaries during welding. At the same time, this steel has improved deep drawability and weldability, and its corrosion resistance is close to that of SUS 304. R 430 LN is a steel developed by adding niobium in place of titanium and is used mainly in parts that require corrosion resistance and weldability, such as bicycle rims.

R 430 CuN was developed without adding expensive molybdenum for applications where bright annealed finished products are required in terms of decorative performance. In this steel, the carbon and nitrogen contents of SUS 430 are lowered, the remaining carbon and nitrogen are stabilized using niobium, the chromium content is increased by 2%, and 0.5% copper is added. The corrosion resistance of R 430 CuN is better than that of SUS 434 (17% Cr–1% Mo), not to mention SUS 430, and can compare with that of SUS 304 in some cases. Furthermore, R 430 CuN is by far superior to SUS 430 and SUS 434 in weldability and formability. **Table 3** and **Figs. 5** and **6** give comparisons of corrosion resistance between this steel grade and the conventional stainless steels. The range of its use is increasing in automobile decoration, kitchin utensils, household electric appliances, building materials, showcase parts, etc.

R 430 LNM is a low-carbon niobium-bearing stainless steel containing 0.5% Mo, compared with R 434 LN-1 containing 1% Mo and R 434 LN-2 containing 2% Mo as will be described later. The pitting corrosion resistance and crevice corrosion resistance of R 430 LNM are almost equivalent to those of SUS 304. **Figures 7** and **8** compare pitting corrosion resistance between R 430 LNM and conventional stainless steels. This steel is finding wider application in fields where corrosion resistance is required, such as hot water boilers (with sacrificial anodes) and their outer panels. The inexpensiveness of this steel promotes this trend.

Table 3 Corrosion resistance of R 430 CuN[a)]

Designation	CASS test[b)]	Salt spray test[c)]	SO_2 test[d)]	Pitting potential[e)] (mV vs. SCE)	10% $FeCl_3$ test[f)]
R 430 CuN	9.6	10~9.8	9.4	222	13.18
SUS 430	9.4	9.8	8.2	122	26.55
SUS 434	9.5	10~9.8	9.4	153	—
SUS 304	9.8	10~9.8	10	336	12.04

Notes a) Bright annealed sheet of 0.4 mm thick
b) JIS D 0201 (49°C, 16 h spray + 8 h rest, 3 cycle)
c) JIS Z 2371 (5% NaCl, 35°C, 500 h)
d) DIN 50018 SFW 2.0 S (40°C, 8 h)
b,c,d) corrosion resistance in estimated by rating number
e) #600 polish, JIS G 0577 (3.5% NaCl, 30°C)
f) JIS G 0578 (35°C, 48 h), corrosion resistance is estimated by corrosion rate ($g/m^2 \cdot hr$)

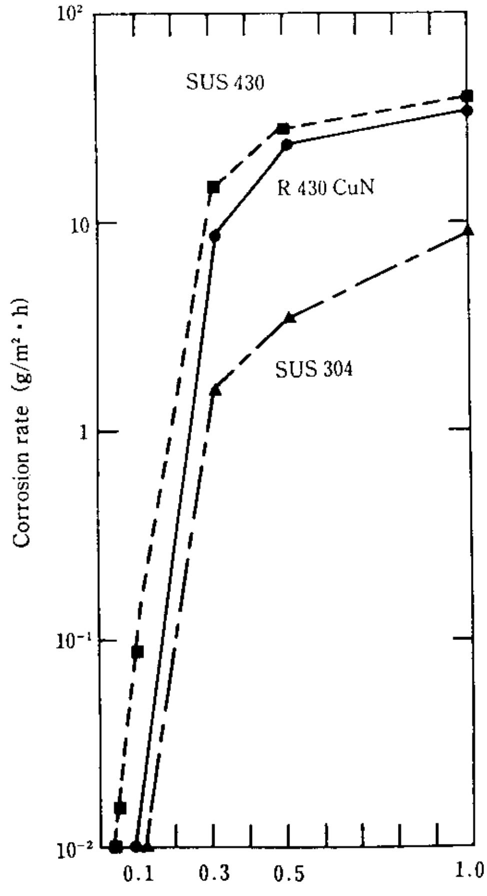


Fig. 5 Corrosion resistance in boiled dilute HCl solution

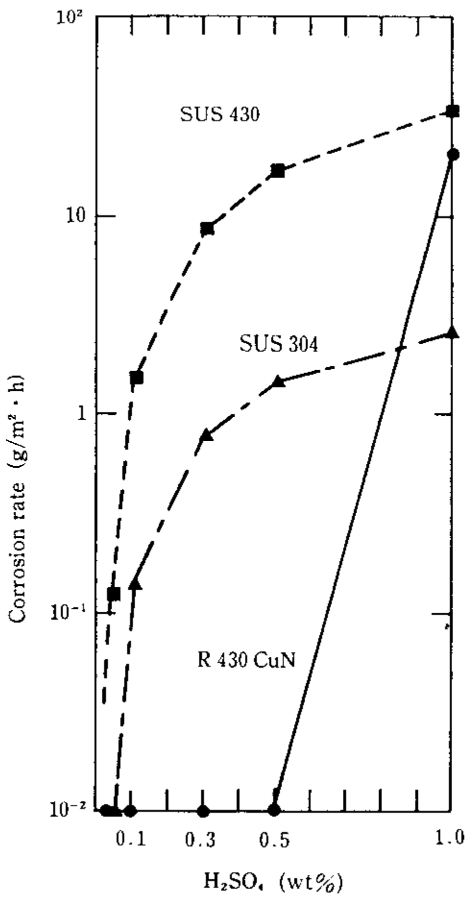


Fig. 6 Corrosion resistance in boiled dilute H_2SO_4 solution

In **R 434 LT-1** and **R 434 LN-1**[11], the carbon content of SUS 434 is lowered to a very low level and titanium or niobium is added to stabilize the remaining carbon. These two steels have corrosion resistance equal to that of SUS 304 and better weldability and formability than SUS 434. Although the basic compositions of **R 434 LT-2** and **R 434 LN-2**[12] were developed by Climax Molybdenum Co., Kawasaki Steel has succeeded in the mass production of these two steels early by SS-VOD techniques. As shown in **Fig. 9**, their corrosion resistance is equivalent to that of SUS 316 and they have so far been used in many applications related to hot water, such as a solar water heating device, inner chamber of electric pot and hot water boiler. According to the results of dip tests on crevice corrosion specimens prepared by spot welding and exposed in hot water of 100 ppm of Cl^- at 80°C for 23 weeks, pitting corrosion and intergranular corrosion occurred in SUS 430, pitting corrosion in R 430 LT and R 434 LN-1, and stress corrosion cracking in SUS 304, whereas any obvious corrosion did not take place in R 434 LN-2 and SUS 316.[16,17]

There are high-chromium molybedenum stainless steels as higher-grade ferritic stainless steels. As men-

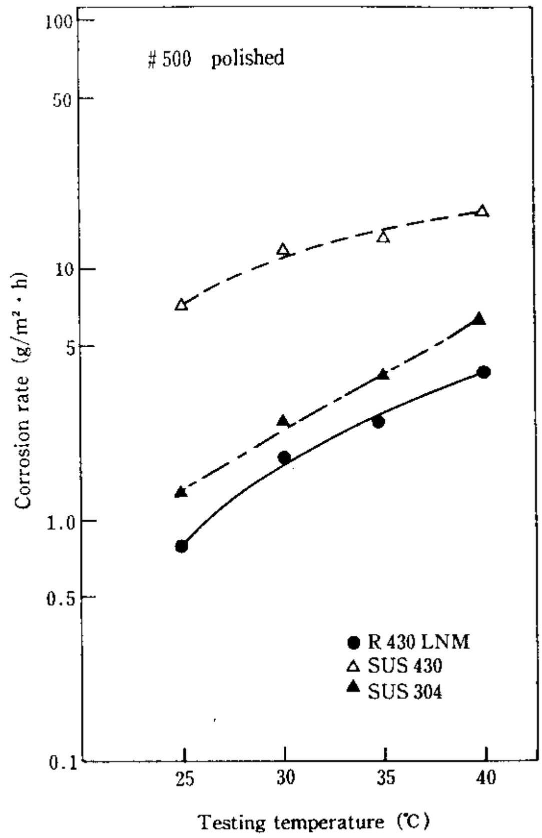


Fig. 7 Corrosion resistance in 10% $FeCl_3$ $6H_2O$ solution for 4 h

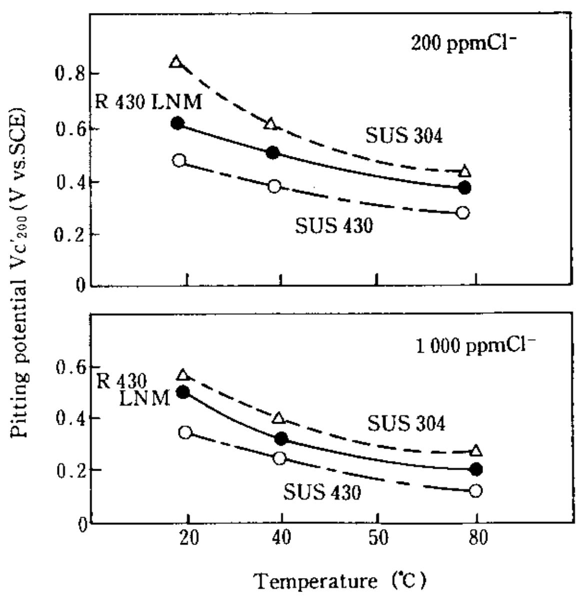


Fig. 8 Pitting potential in 200 ppm & 1000 ppm Cl^- aquious solution

tioned earlier, Kawasaki Steel established an excellent decarburizing technique called the SS-VOD process and entered this field with the cooperation of the Showa

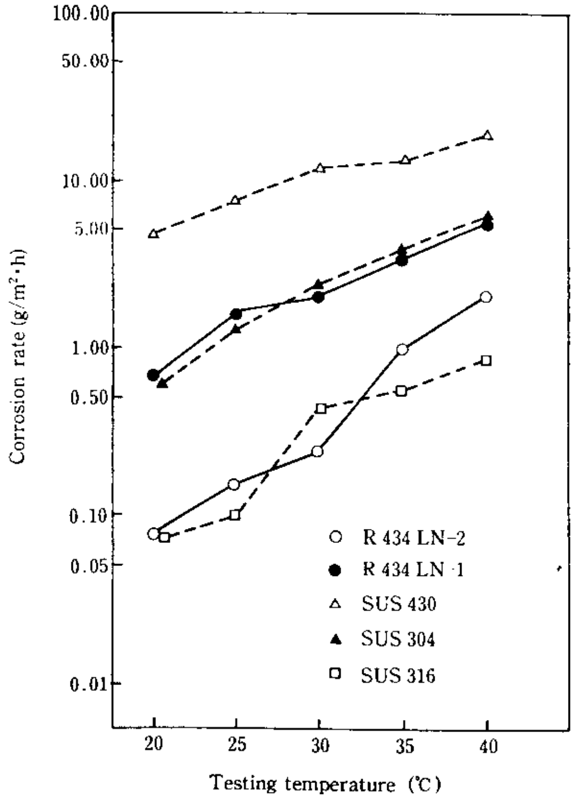


Fig. 9 Pitting corrosion resistance in 10% $FeCl_3$ $6H_2O$ solution for 4 h

Denko K. K. Kawasaki Steel has succeeded in the mass production of the **SHOMAC 30-2** (30% Cr-2% Mo steel) industrialized by Showa Denko K. K. and developed **SHOMAC · RIVER 26-1** (26%Cr-1%Mo steel) and **SHOMAC · RIVER 26-4** (26%Cr-4%Mo steel), both niobium-stabilized ultralow-carbon steels. The application of these steels is widening steadily in chemical plants and other fields where high corrosion resistance is required[18,19] (**Table 4, 5, and 6**).

Table 4 Corrosion resistance in inorganic acids[18]

(g/m²·h)

Steel	65%HNO_3 B.P.	5%H_2SO_4 B.P.	0.5%HCl B.P.	1%HCl B.P.
SHOMAC RIVER 26-1	0.104	0.28	0.05	53.8
SHOMAC 30-2	0.005	0.20	0.044	0.55
SUS 316L	0.028	4.98	9.42	16.2
SUS 304L	0.144	183.0	7.11	12.2

Table 5 Corrosion resistance in organic acids[18]

(g/m²·h)

Steel	80%CH_3COOH B.P.	50%HCOOH B.P.	10%$(COOH)_2$ B.P.
SHOMAC RIVER 26-1	0.00	0.09	0.34
SHOMAC 30-2	0.00	0.07	0.14
SUS 316 L	0.19	0.45	0.86
SUS 304 L	0.29	0.46	—

Table 6 Corrosion resistance in alkaline solution[18]

(g/m²·hr)

Steel	30%NaOH+10%NaCl +0.05%$NaClO_3$, 90°C*	50%NaOH+5%NaCl +0.05%$NaClO_3$, B.P.**
SHOMAC RIVER 26-1	0.016	0.13
SHOMAC 30-2	0.007	0.019
SUS 316L	0.13	3.2
SUS 304L	0.095	—
Nickel	—	0.023

Notes * Corrosive environment of 2nd evaporator in actual caustic soda manufacturing process
** Corrosive environment of 1st evaporator in the same process

3.2 Martensitic Stainless Steels

As represented by SUS 410 and SUS 420 J1 and J2, martensitic stainless steels have high carbon contents. These conventional stainless steels subjected to heat treatment have been used in applications where hardness is mainly required, such as cutting tools. In recent years, however, **R 410 DH**[20] and **R 410 DB**[21] have been developed. In R 410 DH, improved toughness of the welded joint is obtained by utilizing the characteristic of low-carbon martensite, which is the matrix structure of an ultra-high-strength steel (a maraging steel). In R 410 DB, improved corrosion resistance and heat treatment efficiency are attained by utilizing the characteristics of this maraging steel.

Structural steels are generally required to provide sufficient strength in addition to good formability. R 410 DH is a stainless steel for welded structure in which the carbon content is reduced to give toughness to welded joints and the austenite phase which has become unstable at high temperatures due to this decarburization is compensated for by enriching manganese and copper to ensure thorough martensitic transformation. Incidentally, **Fig. 10** shows hardness changes of a welded joint made by TIG welding of 2-mm thick sheets of this steel without filler. The structure of the weld metal is martensite and the heat-affected zone shows a dual-phase structure of martensite and ferrite; these structures are finer than that of the base metal. Therefore, the hardness of

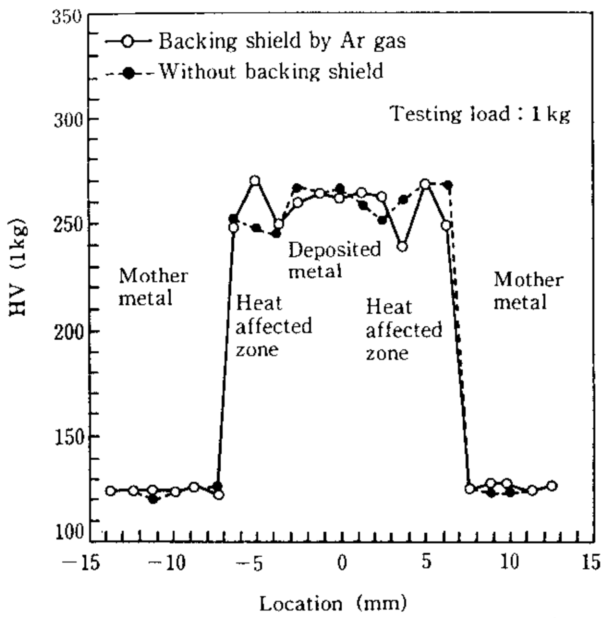


Fig. 10 Vickers hardness of TIG welded joint of 2.0 mm thick R 410 DH

the deposited metal and heat-affected zone is as high as about 260 HV. Their Charpy impact value is 15 to 20 kgf·m/cm^2 at −20°C, which is equal or higher than that of the base metal. This steel is currently used mainly as a cargo container structural material.

HCS 16 is a 16% Cr steel developed with the cooperation of Honda Motor Co., Ltd. Along with AISI 420 J2, it has long been used in disk brakes of two-wheeled vehicles. These conventional steels had been subjected to two-stage heat treatment of quenching and tempering at brake manufacturers to obtain proper hardness for disk brakes. Furthermore, the precipitation of chromium carbides had occurred during tempering due to

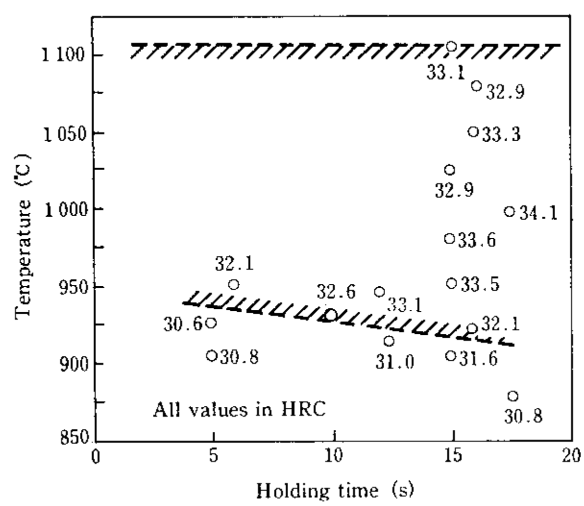


Fig. 11 Relation between quenching conditions and hardness of R 410 DB (cooling rate 30°C/s)

high carbon contents and there had been a problem in corrosion resistance. To solve these problems, R 410 DB was developed. This steel was so designed that hardenability was ensured by lowering the carbon plus nitrogen contents of SUS 410 to 0.04~0.07% and by enriching manganese so that required hardness could be attained by only quenching in the brake manufacturing process. The quenching of disk brakes generally involves high-frequency induction heating. As shown in **Fig. 11**, this steel grade shows almost constant quench hardness in a wide range of heating temperature and holding time. Thus it is possible to carry out the heat treatment process stably. At present, this steel grade is replacing the conventional ones as the material for disk brakes.

3.3 Austenitic Stainless Steels

The most common steel grade of all austenitic stainless steels is SUS 304. The stainless steel produced in the largest amount at Kawasaki Steel is SUS 304. This stainless steel is used in various fields, such as buildings, industrial machinery, kitchen utensils and bath-tubs, demonstrating good corrosion resistance and formability. However, this steel has the drawback that stress corrosion cracking[22] usually occurs in locations where tensile stresses exist, such as the welded joint, when exposed to the corrosive environment at above 60 to 70°C. To eliminate this drawback, **R 304 Cu** and **R 304 CuL** were developed by adding copper to SUS 304 and thereby improving this steel[23]. It has been demonstrated that stress corrosion cracking does not occur in spot welded specimens of R 304 Cu and R 304 CuL exposed at the interface of air and 1000 or 21000 ppm Cl^- aq. solution at 80°C for eight months (under the same condition typical stress corrosion cracking occurs in SUS 304 and SUS 316). Satisfactory results were obtained also from a two-year full-scale test, which was conducted by making a 1500-*l* hot water storage tank of full water type.

The possibility of one-piece drawing of bathtubs became an issue in the past and **R 304 UD** was developed to improve press formability.[24,25] This steel is used in the deeper portion of a double sink and the one-piece drawing of bathtubs is not currently conducted for various reasons. The press formability of this steel for the 2B finish of 0.7-mm thick sheets is 14.1 mm (about 12.5 mm with SUS 304) in terms of Erichsen value and 26.5 mm (27.4 mm with SUS 304) in terms of CCV.

R 304 MN is a steel in which the nickel content of SUS 304 is saved, with manganese and copper enriched to reduce the cost. R 304 MN has better deep-drawability and bulging property than SUS 304. The application of this steel to springs can be expected because hardness can be ensured by adding nitrogen.

New stainless steels developed by improving SUS 301 are **R 301 L** which is used in stainless steel cars of the

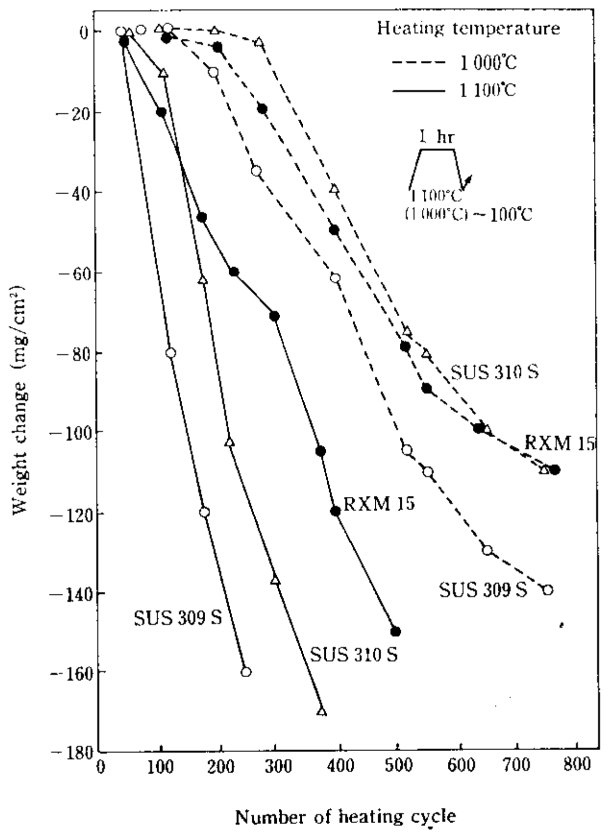


Fig. 12 Weight change in cyclic heating of stainless steels in air

Japanese National Railways and **R 301 R** which is used in automobile springs. The former has replaced the conventional AISI 201 L used in stainless steel cars of U.S. subways, for example, and can fulfil the function required of railway car materials because of its good corrosion resistance in welded structures. The latter was developed jointly with Nippon Kinzoku Co., Ltd. In this steel, the silicon content of SUS 301 is raised, with strain hardening intensified by taking the composition balance into consideration from the standpoint of strain-induced martensitic transformation. Furthermore, the shape, type and size of nonmetallic inclusions are controlled by a special refining method, and fatigue strength is improved to the maximum extent by the cold rolling process.

R 316 LNX was developed by improving the cryogenic properties of SUS 316 related to superconductive technologies such as nuclear fusion, accelerators, superconductive power generation, and power storage. In this steel, the Japan Atomic Energy Research Institute Standards for superconductive magnet core materials are met by adding vanadium and nitrogen to SUS 316. This steel has excellent properties that do not permit embrittlement at cryogenic temperatures even if heat treatment at 700°C for 50 h is carried out to make superconductive materials such as Nb_3Sn by precipitation.[26]

RXM 15 was developed as a steel with better high-temperature oxidation resistance and strength than R 409 SR for use in automobile exhaust gas cleanup equipment (thermal reactors). SUS XM 15 J_1 was later adopted in the JIS Standards as a similar steel grade. In RXM 15, oxidation is prevented by adding silicon to SUS 309 to form SiO_2 film at the interface between the steel base and scale. Furthermore, the adhesion of scale to the steel base is increased by adding REM to prevent the exfoliation of scale that serves as a protective film. **Figure 12** shows a comparison of oxidation resistance between RXM 15 and conventional stainless steels.

4 Concluding Remarks

The manufacturing process of stainless steels at Kawasaki Steel and their properties, especially new products developed by the company have been described.

Stainless steels will find increasingly wide applications in the future because of their characteristics, such as corrosion resistance, heat resistance, and beautiful appearance. Manufacturers must be prepared, however, for the day when requirements for the cost, quality, and properties of stainless steels will become severer against this background. Kawasaki Steel intends to develop new manufacturing processes by using low-cost raw materials and utilizing production facilities used for carbon steels, while making greater efforts in developing new products that will meet diverse requirements of users.

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