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Steinless Steel and Steel Platel

Stainless Steel Production Technologies at Kawasaki Steel －Features of Production Facilities and Material Developments－

Tatsuo Kawasaki

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Kawasaki Steel has careers of more than 40 years in stainless steel flat rolled products. History of the company in terms of production facilities and developments of stainless steel is described. Features of the latest facilities are also described. Significant points are steelmaking process of Cr-ore smelting reduction with combined blowing converter, powerful hot rolling mill, highly efficient cold rolling with cluster and tandem rolling mills. Using these facilities, Kawasaki Steel produces many characteristic stainless steels, especially of super ferritic grades. Corrosion resistance, press formability, oxidation resistance and other performances of developed steels, named "River Lite" series, are explained briefly.

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Tatsuo Kawasaki
Chief Researcher, Technical Service Center, Kawasaki Steel Techno-research Corp. Former Staff General Manager, Stainless & Special Steel Business Planning Dept.

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1 Introduction

Kawasaki Steel now has a history of more than 40 years in the production of stainless steel. The starting point for stainless steel production was the manufacture of hot-rolled sheets which began at Nishinomiya Works in 1954 using a high frequency electric induction furnace and a pull-over type mill for speciality carbon steels. A full-scale mass production system was completed following the installation of rolling, annealing, pickling, and other equipment at Nishinomiya Works in 1962, and both facilities and production capacity were then expanded in line with the high economic growth of the following years. The stainless steelmaking division was moved to Chiba Works in 1981, marking a new start in stainless steel production. A new cold rolling shop, a new steelmaking shop, and a new hot rolling mill were constructed at Chiba Works giving the company two production bases, with an integrated production capability from steelmaking to cold rolling at Chiba Works in eastern Japan, and facilities for producing cold rolled products at Nishinomiya Works in the west. Today's production equipment and the development of new stainless steels can be seen against the background of the various technologies which the company has cultivated over this 40 year period. This report presents an outline of the trends in main equipment and the features of the most advanced equipment and newly developed steel types, as shown in **Table 1**.

2 Features of Production Equipment and Technologies

2.1 Steelmaking Process

Large scale steelmaking of stainless steel started in earnest at Kawasaki Steel with the installation of a 40 t electric arc furnace (EF) at Nishinomiya Works in 1966. The company first adopted ingot casting (IC), which was followed by pressure casting (PC) of austenitic grade steels. In 1971, a vacuum oxygen decarburization (VOD) furnace was introduced, and a process for ferritic grades by the EF-VOD-IC route was established. The company began producing martensitic grade Cr steels by the LD converter (LD)-RH-CC at Chiba Works No. 1

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Table 1 Stainless steel history of Kawasaki Steel

Year	Main facility installed	Developed steel	Note
1954			Start of production of stainless steels using facilities for specialty carbon steels (castings and hot bands)
1955			Start of cold rolled flat products
1956		Tri-ply clad steel	
1962	(N) No. 1 Zr, CB, GR, Bell F, No. 1 AP		Start of mass production of stainless steels at Nishinomiya Plant Start of hot rolling with hot strip mill at Chiba Works
1964	(N) No.2 AP		
1966	(N) No.1 EF		
1967	(N) No. 3 AP		
1968	(N) No. 2 EF, PC, No. 2 CB, No. 1 BA, No. 2 Zr		
1971	(N) VOD, ASEA-SKF		
1972		R430LT	Registration of trade mark as "River Lite"
1973	(N) No. 3 Zr		Start of steelmaking at Chiba Works (LD/RH/IC, CC)
1975	(N) No. 4 AP		
1976		9 new River Lite series developed	Establishment of SS-VOD technology
1977		R304UD, R301L	
1978		R30-2	
1981	(C) MF, KBOP, VOD (Transferred)		Shut down of Nishinomiya EF, and steelmaking transferred to Chiba Works in full production (MF)-KBOP-RH(orVOD)-CC
1982		R409L, R410DH	Start of type 409 production by tandem mill rolling
1983	(C) HAP (Transferred)	R410DB	Transference of No. 4 AP from Nishinomiya Plant to Chiba Works
1985	(C) Coil Box		Commercial production of R409L with Ta-mill
1986	(N) No. 2 BA	R20-5SR	Start of smelting reduction of Cr-ore pellet (SR-KBOP-RH-CC) Start of foil rolling with Zr mill
1988	(C) CAL/Pic		
1990	(C) SCM		
1991	(C) CAP	R315CX	
1992	(C) Finishing facilities	R445MT, R304S	Establishment of production process for bright grade at Chiba Works
1993		R429EX, R20-5USR, R436LT, R432LTM, R439	
1994	(C) SR, DC, VOD, CC	R430UD, RSX-1, R430XT	Start of smelting reduction of Cr-ore sand
1995	(C) No. 3 Hot		
1996			(N) Revamping of No. 1 Zr for foil rolling

(N); Nishinomiya Plant, (C); Chiba Works, R; River Lite
Zr; Sendzimir mill, Hot; Hot strip mill, CB; Coil build-up, GR; Coil grinder, Bell F; Bell type furnace, AP; Annealing and pickling
EF; Electric arc-furnace, PC; Pressure caster, BA; Bright annealing, VOD; Vacuum oxygen decarburization
IC; Ingot casting, CC; Continuous caster, SS-VOD; Strongly stirred VOD, MF; Electric arc melting furnace
KBOP; Kawatetsu blowing oxygen process, HAP; Hot band AP, SR; Smelting reduction, DC; De-carburization

steelmaking shop in 1973, and was able to evolve this process into production by the top and bottom blowing converter (KBOP)-RH-CC in 1981. (With austenitic grades, the melting furnace (MF)-KBOP-RH-CC route was used.) Both Chiba Works and Nishinomiya Works continued to operate steelmaking processes until the EF at Nishinomiya Works was shut down in 1981, and during this period, the strongly stirred VOD (SS-VOD) was developed and a refining technology for ultra low C + N was completed. The period that followed was characterized by the smelting reduction furnace (SR)-KBOP-RH-CC process using pre-reduced Cr ore pellet at Chiba Works No. 1 steelmaking shop. However, in 1994, No. 4 steelmaking shop was constructed, and an SR-decarburization furnace (DC)-VOD-CC process which uses raw Cr ore has now been realized. This offers an sharp contrast to the EF-AOD(or VOD)-CC process which is employed by virtually all other stainless steel makers in the world.

An outline of the stainless steelmaking process at No. 4 steelmaking shop[1,2] is shown in **Fig. 1**. In the smelting reduction furnace (SR-KCB; Kawatetsu combined blowing converter), Cr ore is melted and reduced, using as the main materials pretreated hot metal together with

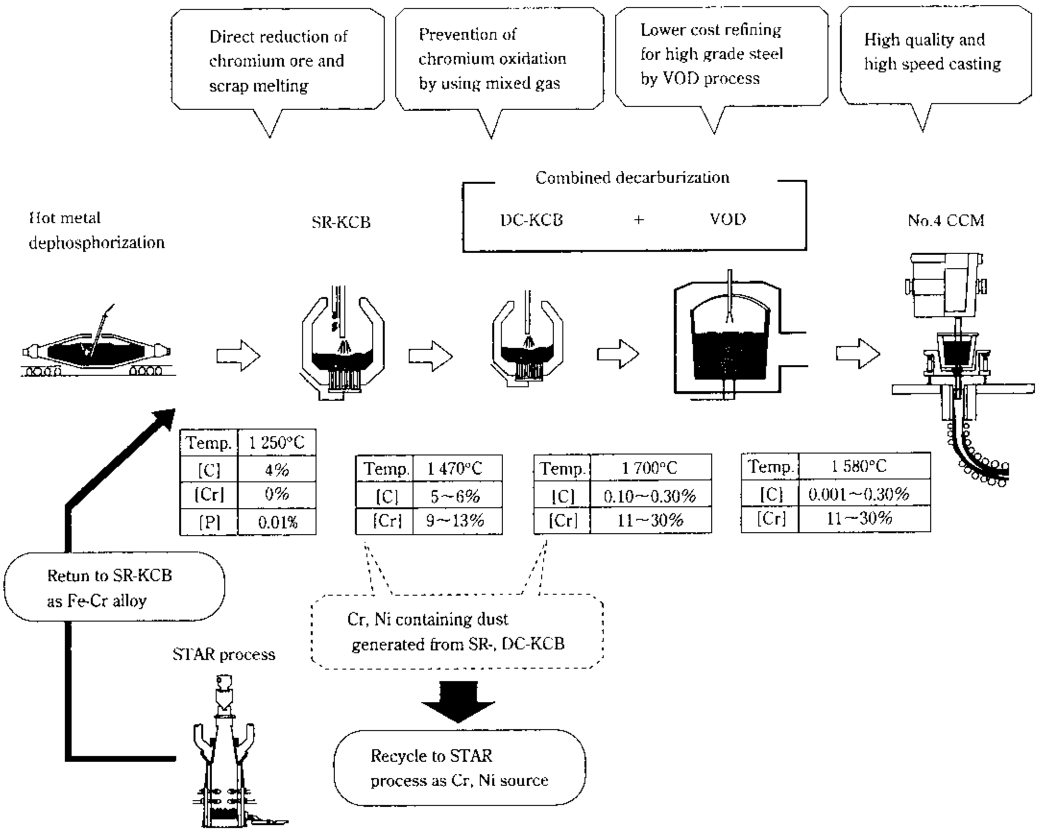


Fig. 1 The latest outline of stainless steelmaking process

scrap and recycled metal recovered by the STAR (stainless advanced reactor) process, which chemically reduces converter dust. The molten steel is then tapped once, Fe-Cr, Ni alloy, and scrap are added, and high speed decarburization is performed in the decarburization furnace (DC-KCB) by dilution gas blowing. The product is finished as ultra-low C + N by VOD. Because the SR-KCB is a large capacity furnace, it is possible to add raw Cr ore in powdery form directly from the lance, and to melt scrap in large quantities. Both the smelting reduction furnace and the decarburization furnace are top and bottom blowing converters in which coal is blown from the top lance and a strong stirring force is realized by high flow rate blowing from the bottom blowing tuyeres. In the bottom blowing tuyeres, double-walled tubes are used, making it possible to below O_2 diluted with Ar or N_2 from the inner tube while blowing propane gas from the outer tube. The VOD has a ladle with a capacity of 178 t. Bottom blowing type stirring using a high flow rate slit plug and high vacuum control during decarburization treatment using the strong exhaust capacity of a two stage booster and two stage parallel ejector make it possible to perform high speed decarburization and denitrogenation. To improve productivity, a twin tank method has been adopted, in which the treatment under vacuum condition and treatment

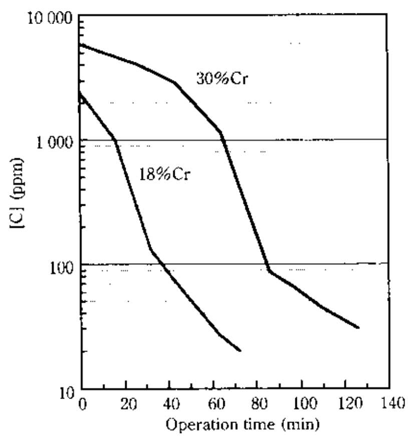


Fig. 2 Results of VOD operation for super ferritic stainless steel

under atmospheric pressure condition are separated. An example of the decarburization treatment of 18% Cr and 30% Cr by VOD is shown in **Fig. 2.**[1] Even with large heat sizes, an adequate decarburization speed is obtained.

In continuous casting,[3] a large centrifugal flow (CF) tundish is used as a countermeasure against inclusions, and a vertical bending type caster has been adopted. The

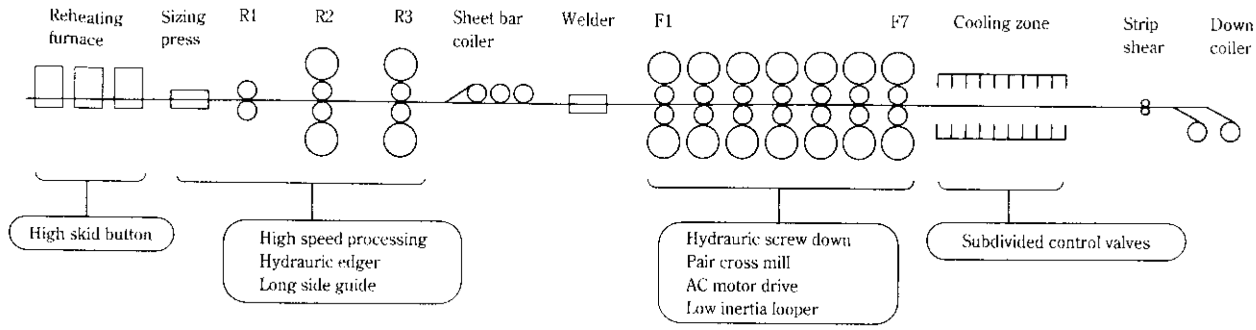


Fig. 3 Layout of No. 3 hot strip mill

length of the vertical section is 2.5 m. The slab sizes range in thickness from 200 to 260 mm and have a maximum width of 1 650 mm. The maximum casting speed is 1.60 mpm with SUS304 and 1.55 mpm with SUS430, which are the world's highest speed levels.

2.2 Hot Rolling/Hot Band Annealing and Pickling Process

Hot rolling was originally performed with a narrow-width semi-continuous hot strip mill, but was moved to the Chiba Works hot strip mill when production of wide strips began in 1962. Following the period when No. 1 and No. 2 hot strip mills were used, production was transferred to the newly constructed No. 3 hot strip mill (No. 3 Hot) in 1995. **Figure 3** shows the layout of No. 3 Hot[4]. This facility comprises three reheating furnaces, a 3-stand rougher mill, a sheet bar coiler, a welder, a 7-stand finishing mill, a cooling zone, and two coilers. Among this equipment, the sheet bar coiler and welder are not currently applied to stainless steel. As features of No. 3 Hot, the degree of freedom in setting widths is increased by the sizing press and hydraulic screwdown type edger, resulting in improved width accuracy, and heavy reduction is possible using the mill's powerful motors. In addition, pair cross rolls are adopted in the finishing stands, which improves the thickness profile. Thoroughgoing automation and unmanned operation have been incorporated in all the sections from the slab yard to the coilers[5], so that only three operators are now responsible for the operation in the general control room.

Because it is now easier to optimize the slab heating temperature, reduction ratio settings in roughing and finishing rolling, and coiling temperature, material design of hot bands which provide excellent formability after cold rolling has become possible.

Hot band is annealed and descaled by the hot annealing and pickling (HAP) line (SUS430 is batch annealed). This equipment was moved from Nishinomiya Works No. 4 AP in 1984, and originally was a combination line for both hot and cold strips. However, when the line was revamped as an exclusive use facility for the hot strips, extra pickling tanks and scale breaker were introduced and the capacity of the line was expanded. At present, this facility has a production efficiency exceeding 60 t/h, and thus has the world's highest level of capacity for a single annealing and pickling line.

2.3 Cold Rolling/Annealing/Finishing Process

2.3.1 Bright finished products

Bright finished (2B, BA) products are rolled using the Sendzimir mills (Zr) and 12-high cluster mill.

The Zr mill was introduced at Nishinomiya Works in 1962. The company currently has three Zr mills, which are used in manufacturing BA and 2B products with thicknesses of under 0.5 mm. By optimizing the roughness of the second intermadiate rolls of the Zr mill, it is possible to suppress chattering and obtain products with high surface quality.[6] With BA products, scratches can occur due to center buckling during cooling at the wide width vertical BA furnace. However, this problem is prevented by rolling profile control in which quarter buckling is suppressed by optimizing the roll curve and other improvements. With 2B products, whiteness is reduced and high brightness is maintained during rolling by optimizing electrolytic descaling in a neutral acid solution in finishing pickling.[7]

Production of bright finished products at Chiba Works began with the installation of the stainless cold mill (SCM) and cold strip annealing and pickling (CAP) line in 1991.[8] Because the SCM was introduced to maintain a high level of quality in dimensions, shape, and brightness and to achieve high speed rolling and automation, a 12-high cluster mill was adopted. This mill has the capability to roll at a maximum speed of 800 mpm with a maximum width of 1 600 mm. To ensure quality at the CAP, cleaning equipment was provided at the entry side of the annealing furnace, and in descaling, electrolytic descaling in a neutral acid solution and $HNO_3 + HF$ was adopted, enabling high speed operation. In electrolytic descaling in a neutral acid solution, a trans-tank setting of the electrodes is used and brushes are installed between the tanks. The pickling solution circulates between the pickling tanks and a reserve tank, and its concentration is controlled by automatic analysis. As to the composition of the line, in order to improve productivity, in-line equipment was adopted for the skinpass mill, tension leveler, and trimmer so that the finishing function is incorporated in the line itself. The leading and tail ends of coils are cut automatically off based on information from an automatic defect detection device.

2.3.2 Functional stainless steels

In anticipation of a changeover from aluminum coated steel to stainless steel as the material for automotive exhaust systems, Kawasaki Steel began rolling AISI409 on the tandem (Ta) mill. As early as 1982, the company took the lead in producing stainless steel using equipment for carbon steel. Thereafter, the company promoted the composition design for R409L, and in 1988, extended this approach as expected to production using the continuous annealing line (CAL) for carbon steel. The annealing atmosphere in the CAL is HNX, which is not a problem with carbon steel, but pickling is necessary in order to remove a scale on 11% Cr, even though this material is a heat resisting steel the oxide film generates on the surface. For this reason, the company developed a high speed descaling method (CAL/Pic),[9] in which in-line pickling treatment is performed with the CAL. This is a method of electrolysis treatment in a mixed acid of nitric and hydrochloric acids, and has made it possible to perform pickling in an extremely short time of 1.6 s under the acid conditions shown in **Fig. 4**. This process has been applied to all muffler grade steels among exhaust system materials, as will be discussed in the following.

The most important feature of the Ta-CAL/Pic process is the high productivity of Ta rolling, which completes rolling in a single pass, and the CAL, which makes it possible to perform annealing and pickling in one line at a high speed. Comparing the productivity of Zr and Ta rolling and the CAP and CAL/Pic processes,[10] 8–10 times higher rolling productivity can be obtained with the Ta, and 2–4 times higher annealing/pickling productivity can be obtained with the CAL/Pic.

2.3.3 Stainless steel foils

Stainless steel foil[11] are enjoying increasing demand as a catalyst substrate for after treatment of automotive exhaust gas, and it has become possible to roll extremely thin foils as a result of improvements in the Zr mill. The most important technical tasks were preventing wrinkles and breaking of the foil. Foil production began in 1986 at Kawasaki Steel's Fukiai Works. Following the Great Hanshin-Awaji Earthquake which struck Kobe in 1995, No. 1 Zr mill at Nishinomiya Works was revamped in 1996. At present, the main product rolled on this mill is 20Cr-5Al steel. Rolling at a width of 1 m is possible in thickness as thin as 30 μm. Finishing annealing is performed with a horizontal type BA furnace (No. 2 BA) which is used exclusively for foil.

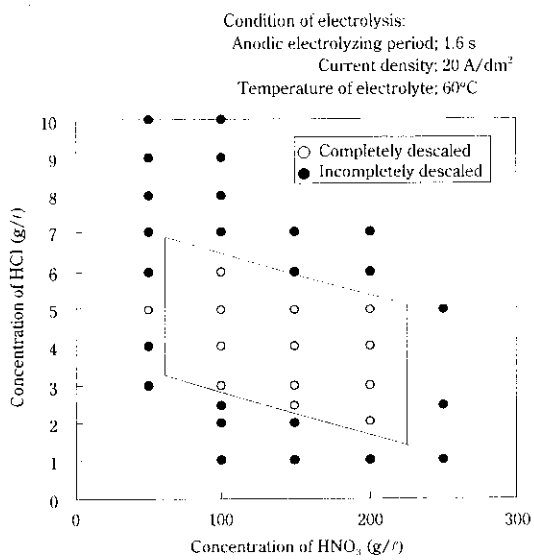


Fig. 4 Optimum range of concentration of HNO_3 and HCl for electrolytic descaling of R409L annealed in CAL

3 Steel Development

The development of high performance steels derived and expanded from the Japanese Industrial Standard (JIS) grades as new products of Kawasaki Steel began with the introduction of VOD in 1971. Riding the wave of high economic growth, materials with high properties not found in conventional steels were demanded in a variety of fields. The development of non-JIS products by Kawasaki Steel was a result of the company's response to this demand. The first of these products to be developed was River Lite 430LT (abbreviated R430LT), which is material for hot water tanks.[12] In this steel type, SUS430 (at the time, SUS24) is given an ultra-low C + N composition and Ti is added as a stabilizing element. The product was marketed as a countermeasure against stress corrosion cracking in SUS304 (formerly SUS27). Subsequently, after the SS-VOD was developed by substantially improving the decarburization and denitrogenation capacity of the VOD process,[13] steel development was expanded to high Cr, high Mo steels which could not previously be used in practical applications due to their inadequate toughness. Beginning with R434LN-2, in which the Mo content of SUS 434 is increased to 2%, a series of 30%Cr-2%Mo steels[14] were developed and marketed. Not only high corrosion resistance materials, but also high oxidation resistance steels such as high Si and high Al, which had been difficult to manufacture from the viewpoint of toughness,[15] high strength with toughness steels of a low carbon martensite,[16] and others are all steel types which take advantage of the features of the SS-VOD process. In the austenitic grades, improvement in corrosion resistance[17] and stress corrosion cracking resistance[18] mainly by alloy design, improvement of press formability[19] by a strain induced martensite formation were promoted. Because the developed steels played the role of answering requirements of the times, production of some products has now been discontinued, whereas others have been improved and their original names have been changed.

The representative steel grades in the River Lite Series are shown in **Table 2**. An outline of the main steel grades by function is presented in the following.

3.1 High Corrosion Resistance, High Anti-atmospheric Corrosion Stainless Steels

Because the corrosion resistance of stainless steels depends on a passivation film, this property is basically determined by the content of Cr and Mo. If the C content is high, a Cr depleted zone[20] will be formed by precipitation of Cr carbides, causing deterioration of corrosion resistance in the heat affected zone after welding. In order to secure corrosion resistance, an ultra low C design is adopted, and Ti and Nb are added as stabilizing elements. In order to reduce the ductile-brittle transition

Table 2 Kawasaki Steel's developed stainless steel "River Lite" series

Characterisitics	Designation	Alloy design	Phase	Process	Main features and applications
Corrosion resistance	R30-2	30Cr-2Mo-Nb	F	Z	The highest corrosion resistance in the series. Applicable to architectures in severe corrosive environments.
	R24-2	24Cr-2Mo-Nb	F	Z	Higher corrosion resistance than type 316. Applicable to architectures in sea side environments.
	R445MT	22Cr-1.5Mo-Ti	F	Z	Comparable corrosion resistance to type 316. Suitable to architectures and hot water applications.
	R434LN-2	18Cr-2Mo-Nb	F	Z	Good corrosion resistance as a substitution to type 316. General use.
	RSX-1	18Cr-1.5Mo-Ti	F	Z, T	Good corrosion resistance as a substitution to type 304. General use.
SCC resistance	R315CX	19Cr-13Ni-3Cu-3Si	A	Z	High SCC resistance. Suitable to hot water equipments.
Deep drawing	R430UD	17Cr	F	Z	Deep drawing quality of type 430 with high unti-ridging property. General use.
	R430XT	17Cr-Ti	F	Z, T	Deep drawing quality with good weldability. Better corrosion resistance than type 430. General use.
	R430LN	17Cr-Nb	F	Z	Same properties as R430XT, with Nb instead of Ti as a stabilizer. General use.
	R304S	18Cr-9Ni-1Cu	A	Z	Low work hardenability and easy forming with low magnetization. General use.
Automotive exhaust availability	R409L	11Cr-Ti	F	Z, T	Standard grade for exhaust systems.
	R439L	18Cr-Ti	F	Z, T	Better corrosion resistance than R409L. Suitable to muffler application.
	R432LTM	18Cr-0.5Mo-Ti	F	Z, T	Improved corrosion resistance of R439L in muffler condensate by Mo addition.
	R436LT	18Cr-1.2Mo-Ti	F	Z, T	The highest corrosion resistance in muffler condensate with 1.2Mo.
	R429EX	15Cr-0.8Si-Nb, Co	F	Z, T	Good formability and high temperature strength. Suitable to hot end application such as exhaust manifold.
Heat and corrosion resistance	R430CuN	19Cr-0.5Cu-Nb	F	Z	Good corrosion resistance and high temperature strength. Suitable to hot water equipment and exhaust manifold.
	R430LNM	17Cr-0.5Mo-Nb	F	Z	Good corrosion resistance and high temperature strength. Suitable to hot water equipment and exhaust manifold.
Oxidation resistance	R20-5USR	20Cr-5Al-La	F	Z	The best oxidation resistance of foil application. Applicable to catalyst substrate and resistant heater.
	R409SR	11Cr-1.5Si-Ti	F	Z, T	Good oxidation resistance with formability and weldability. Suitable to burner application.
Functionability	R410L	13Cr	F	Z, T	Standard grade for general use. Improved formability and weldability by reducing C and N content.
	R410DB	13Cr-1.5Mn	M	H, Z	Stable quenched-in hardness and ductility. Suitable to brake disk of motor cycle
	R410DH	12Cr-1Mn-Cu	F	H, Z	Good HAZ softening resistance. Suitable to weld structural use.
	R301L	17Cr-7Ni	A	Z	High strength and good fatigue property. Suitable to rail way car components and thin spring use.

R: River Lite for short, F: Ferritic grade, A: Austenitic grade, M: Martensitic grade
Production Process H: Hot rolled, Z: Sendzimir mill rolled, T: Tandem mill rolled

temperature when C + N is low, as shown in **Fig. 5**,[21] and thus improve the toughness of the weldment, it is necessary, as might be expected, to reduce the C + N content as far as possible. In addition, this also makes it possible to reduce the amount of stabilizing elements added. Particularly with high Cr-Mo steels, it is desirable from the viewpoint of toughness not to add a larger amount of stabilizing elements than necessary. The pitting potential of the River Lite Series, in which high purification to 150 ppm or under of C + N is obtained by the SS-VOD process, is shown in **Fig. 6**, arranged with Cr + 3.3 Mo (P.I.: pitting index) as a parameter. From R439L to R30-2, the pitting potential is increasing linearly as P. I. increases. RSX-1[22] is a steel type with a composition design which gives the same P.I. as SUS304. RSX-1 is suitable for applications in which SUS304 is necessary for corrosion resistance. When a higher level of corrosion resistance is required, River Lite steels with higher P.I. can be selected as required by the corrosive properties of the service environment.

Figure 7[23] shows the results of an evaluation of the atmospheric corrosion resistance required in construction materials by the rating numbers of the Japan Stainless Steel Association (SARN) when various steels were exposed in environments with differing corrosion condi-

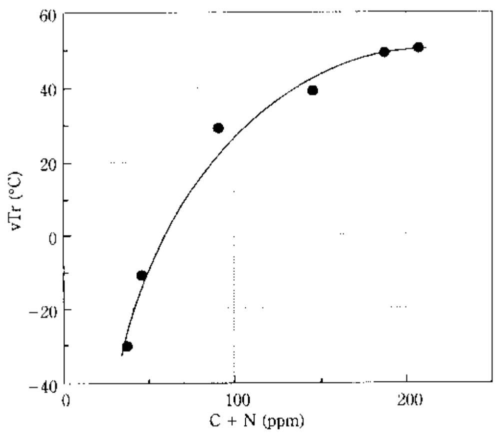


Fig. 5 Effect of C + N content on ductile-brittle transition temperature of 17%Cr stainless steel TIG weldment (3 mm thick hot band)

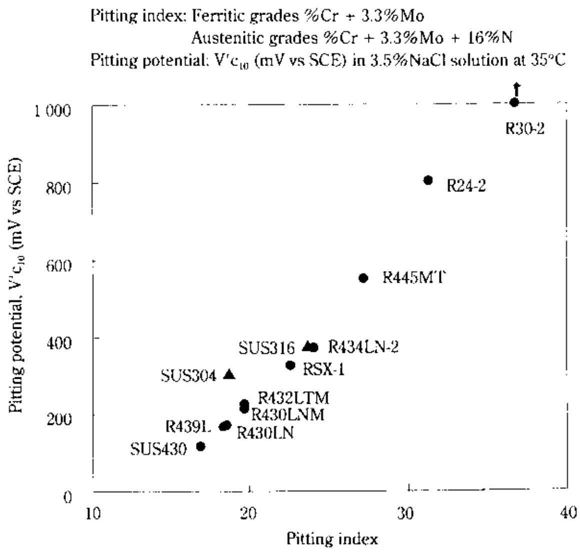


Fig. 6 Relation between pitting index and pitting potenial of stainless steels

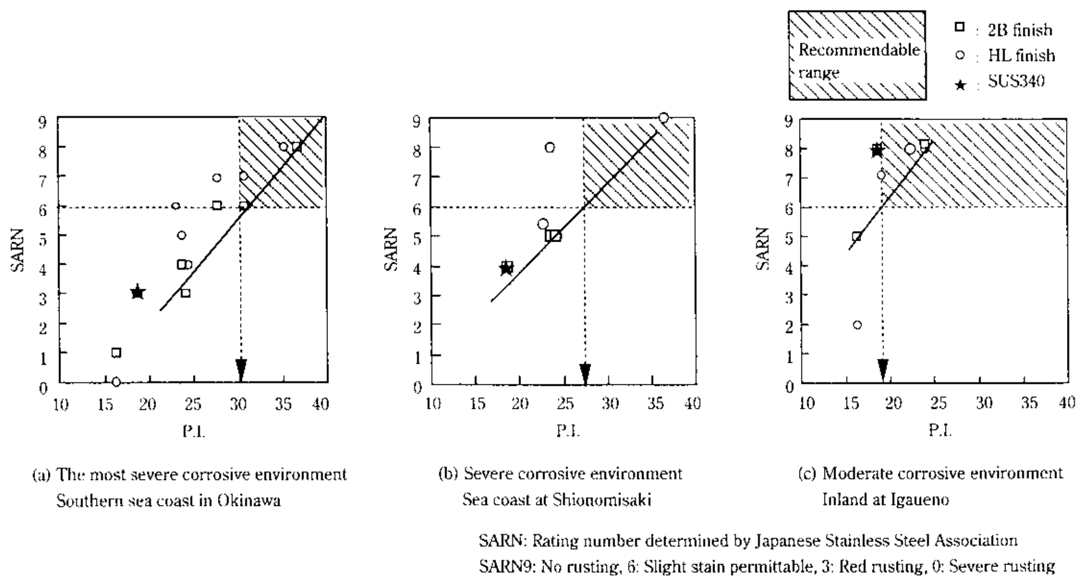


Fig. 7 Relation between pitting index and rusting evaluation of SARN after one year exposure in various environment

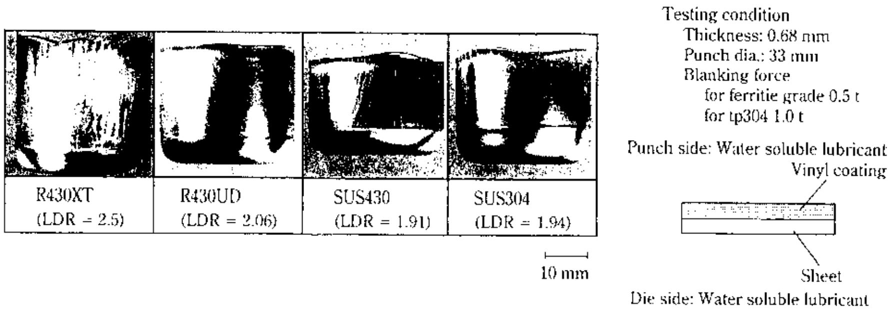


Photo 1 Appearance of ridging and drawn cup-height of R430UD and R430XT after Olsen Cup Test

tions, arranged by P.I. Stainless steels which have a P.I. corresponding to the service environment should be selecting from this figure, assuming that a material is suitable for practical application if its SARN is 6 or higher.

3.2 Stainless Steel with High Formability

Excluding from the detrimental effects of non-metallic inclusions, the press formability of austenitic stainless steels mainly depends on the composition balance, which determines the stability of austenite from which martensite forms.[19] On the other hand, the press formability of the ferritic grade depends mainly on texture, and manufacturing conditions in the hot and cold rolling processes are therefore the governing factors. Ridging after cold rolling and annealing can be minimized and high r values can be obtained by using slabs of steel which has been highly purified in the steelmaking process and performing rolling with the optimum combination of temperature and reduction ratio at No. 3 Hot, which was designed to enable heavy reduction rolling. A product in which this type of treatment is applied to SUS430 was developed under the name R430UD for deep drawing applications. R430LT, which was produced by reducing C + N in SUS430 to ultra-low levels and stabilizing it with Ti, had a high r value and excellent formability, but sometimes showed a remarkable amount of coarse ridging. R430XT was developed by optimizing the chemistry and the hot rolling conditions applied to this steel. As illustrated in **Photo 1**, both of these new products show a high deep drawing property and low ridging. The same type of treatment can also be applied to other steel types in which a deep drawing property is necessary. For example, it was also used as a technique for improving the formability of RSX-1, which has corrosion resistance equivalent to that of SUS304. **Figure 8** shows the level of improvement in ridging and r values obtained by optimizing the hot rolling process.

Ridging countermeasures in the hot rolling process are linked to the suppression of roping during cold rolling, and also are effective in suppressing the formation of oil pits during rolling and improving glossiness of the steel. The effect of TMT (thermo-mechanical

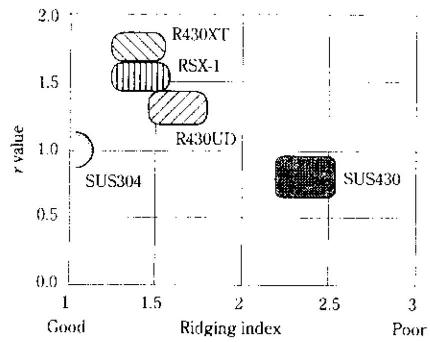


Fig. 8 Commercially available range of r value and ridging grade and r value of R430UD, R430XT and RSX-1

treatment) in the hot rolling process has made it possible to manufacture stainless steel with high quality.

3.3 Stainless Steel with High Oxidation Resistance

Kawasaki Steel energetically promoted the development of stainless steel with high oxidation resistance as a material for use in devices applied as countermeasures against automotive exhaust gas systems in the first half of the 1970s.[24]

The oxidation resistance of stainless steel is determined by Cr and Si or Al. This is analogous to the manner in which Cr and Mo are the controlling elements for corrosion resistance, as oxidation resistance depends on whether or not a stable film composed mainly of the former elements is produced during heating to high temperatures. Because Si has approximately 6 times the effect of Cr, as shown in **Fig. 9**, the parameter for oxidation resistance is Cr + 6Si.

R409SR is a steel type in which the C + N of SUH409 is reduced to an ultra-low level and up to 1.5% Si is added. This product possesses oxidation resistance at temperatures up to approximately 900°C and shows good formability and weldability.[25] If the Si content is increased further, oxidation resistance is also increased, but because scale tends to spall easily and toughness is reduced, the composition is balanced at 1.5% Si. This steel was a forerunner of the high Si ferritic grade oxi-

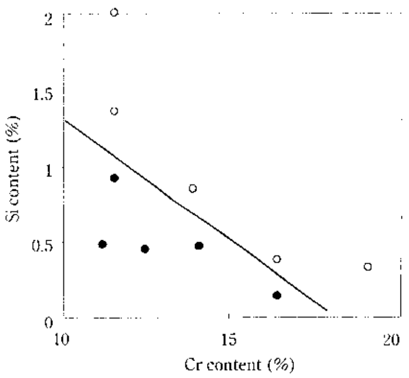


Fig. 9 Relation between Cr and Si content on the oxidation resistance (After oxidation in air at 950°C for 300 h. ● denotes abnormal oxidation.)

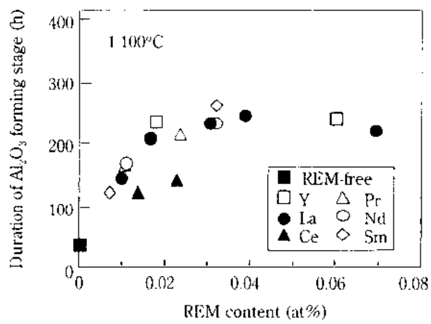


Fig. 10 Effect of rare-earth metals on duration of Al_2O_3 forming stage under oxidation of 50 μm thick Fe-20Cr-5Al alloy foils at 1 100°C in air

dation-resistant stainless steels.

R20-5USR is a 20%Cr-5%Al steel which is used as the catalyst substrate for automotive exhaust gas purification systems by forming foil less than 100 μm in thickness into a honeycomb structure. Fe-Cr-Al alloys had been used from an early date in wire or strip form as resistance heating elements, and in particular, it was known that the addition of rare earth elements is effective in improving the spalling resistance of Al_2O_3 films. However, when the effect of the rare earth elements was investigated in detail, it was found that the Ce in commonly used Misch metal (La + Ce) has little effect, and the effect of La is great.[26] Other lanthanide elements and yttrium (Y) are also effective, as shown in **Fig. 10**.[27] However, these elements are expensive due to their scarcity, and for this reason, simple addition of La is used in R20-5USR. Recent research is continuing to clarify the effect of La in improving oxidation resistance. Namaly, the growth mode of the Al_2O_3 film is the inward diffusion of oxygen, and by segregating at the oxide grain boundaries, La reduces the rate of film growth.[28] Even though this 20Cr-5Al steel has an ultra-low C + N composition, the ductile-brittle transition temperature of the hot-rolled strips is higher than room temperature, and the steel is therefore extremely brittle. However, by applying the know-how which was cultivated in the production of high Cr ferritic grade stainless steels, this steel can now be manufactured as a wide strip using general stainless steel production equipment in all the stages from steelmaking and slab casting to rolling as 30 μm foil.

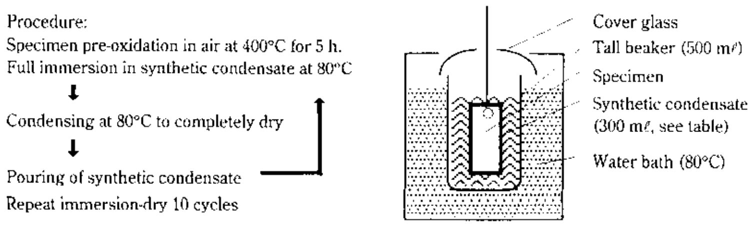
3.4 High Function Stainless Steels

Stainless steels for automobile mufflers[29,30] comprise four types of ultra-low C + N Ti-stabilized steel, namely, 11Cr, 17Cr, 17Cr-0.5 Mo, and 17Cr-1.2 Mo. All of these products are manufactured by the Ta-CAL/Pic process, and are used as required by the corrosion properties of the exhaust system. As shown in **Fig. 11**, the corrosion behavior of these steels in a synthetic condensate is markedly superior to that aluminum coated steel, contributing to longer life of exhaust systems. The Ta-CAL/Pic process is playing an important role in promoting the general use of stainless steel as a muffler material.

In materials for automotive exhaust manifolds, oxidation resistance, high temperature strength, and hot salt corrosion resistance are necessary, and formability is also required in tubes and plates because the material is formed into complex shapes. Oxidation resistance is secured by applying the way of thinking mentioned above, and high temperature strength is obtained by adding Nb and Mo. Because hot salt corrosion resistance is improved by Mo, as can be seen in **Fig. 12**,[31] the composition is designed as required by the use conditions. As mentioned previously, for oxidation resistance at approximately 950°C, the target value for Cr + 6Si is 20. Therefore, considering the fact that stainless steels generally contain approximately 0.5%Si, 17–18% Cr steel is recommended and actually applied. If high temperature strength and hot salt corrosion are considered, an Mo, Nb added steel with high corrosion resistance is appropriate, and in this case, R430LNM, R434LN-2 are recommended and acutually appliied. As a low cost material which does not contain Mo, R429EX,[32] with a 15Cr-0.9Si-0.4Nb composition, has also been developed and applied practically.

All of the above are steels with a composition design based on ultra-low C + N, with features imparted to the product by Kawasaki Steel's production facilities. Several other examples of high function materials are also introduced in the following.

R410DH and R410DB can be mentioned as steels which take advantage of the toughness and corrosion resistance of low carbon martensitic steel. Both are 13Cr steels in which hardenability is obtained by Mn. Cu is added to R410DH and the product is given resistance to temper softening of the heat affect zone by the effect of



(ppm)

Cl^-	SO_3^{2-}	SO_4^{2-}	CO_3^{2-}	NO_2^-	NO_3^-	CH_3COO^-	HCHO	$COOH^-$	NH_4^+	Active carbon
250	1 250	1 250	2 000	100	20	400	250	100	2 500	50 g/ℓ

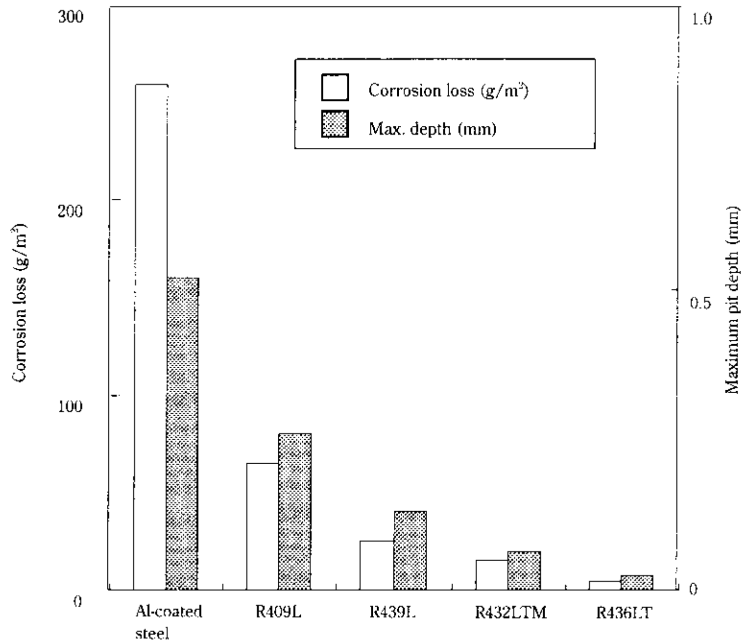


Fig. 11 Corrosion behavior of muffler grade steels in synthetic condensate of muffler

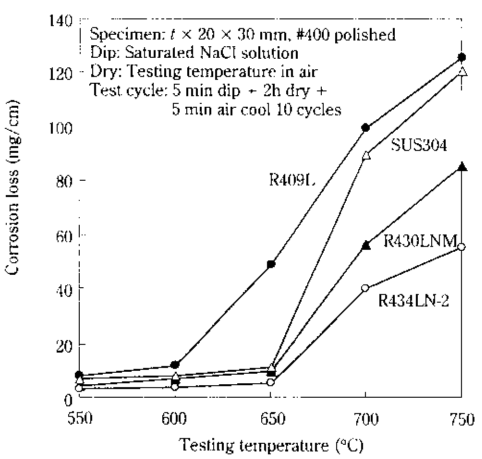


Fig. 12 Corrosion behavior of stainless steels under hot salt corrosion

ε-Cu precipitation, making this steel appropriate for welded structures.[33] With R410DB, strict control of the content of carbon and nitrogen makes it possible to obtain the specified hardness (in this diagram, C + N = 700 ppm, HV350) over a wide temperature range by quenching only, as shown in **Fig. 13**.[34] Because this material possesses excellent toughness in the as-quenched condition, its corrosion resistance is not deteriorated by tempering, and it is therefore suitable for application to motorcycle brake disks. It has earned a favorable evaluation because customers can perform hardening treatment easily, and can also save the cost of tempering.

Although not related to material development, Kawasaki Steel also produces SUS304 checker plate for flooring. By utilizing the powerful hot rolling mill at Chiba Works, this product can be manufactured in a wide range of sizes to a thickness of 2.5 mm and a width of 1 500 mm. The company hopes that this product will achieve widespread use as a clean flooring material.

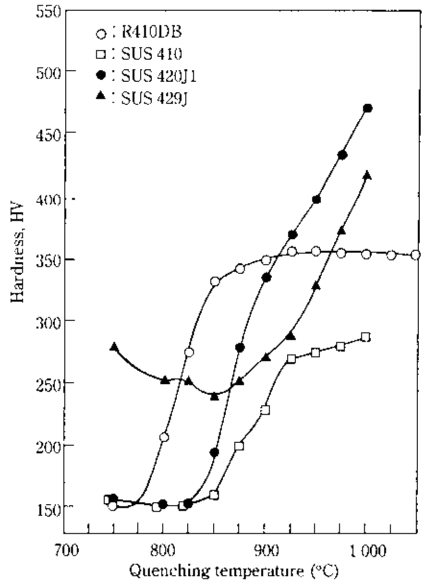


Fig. 13 Relationship between hardness and quenching temperature (Holding time, 10 min; cooling rate, 30°C/s)

4 Conclusion

An outline of Kawasaki Steel's production technologies for stainless steel from steelmaking to finishing has been presented. It is hoped that the company's stainless steel manufacturing process based on the functions and distinctive features of the respective equipment will be understood. Representative examples of newly developed products which are made possible by this equipment have also been introduced. By continuing to develop innovative new production processes and materials, Kawasaki Steel will continue to respond to the needs of customers in the new century, as it has in the past, and hopes to develop a line of distinctive, high quality stainless steels which customers will choose because they bear the Kawasaki Steel name.

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