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Development in the Quality and Designability of Stainless Steel Sheets

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This paper summarizes developments in the quality, designability, and multi-functionability of stainless steel sheets. The corrosion resistance of stainless steel has been improved by controlling alloying elements in two ways. The first is to reduce carbon to an extra-low concentration, and the second is to increase the content of alloying elements. Also described are improvements in the oxidation resistance and quench-hardenability of stainless steel for disk brake use. For designability, two coloring methods of stainless steel have been developed. One is the electrochemical oxidation to form a thin film and the other is the transparent resin coating on the surface of stainless steel. Stainless steels also attained multi-functionability by developing products for far-infrared radiation, for a catalyst substrate to be used in automobile exhaust systems, and for nonmagnetic application.

1 Introduction

It is not intrinsically necessary with stainless steel to coat a rust-preventive over the surface because of the excellent corrosion resistance provided by this material. For this reason, stainless steel is normally used without coating, so that better surface quality is a more important requirement for stainless steel than for ordinary steels. Further, as stainless steel is expensive, it is often given hair-line processing, fish scale polishing, mirror polishing, or other cosmetic processing to emphasize the metallic brightness of the surface and thus express a feeling of higher-quality. At the same time, this relates to the demand that the attractive metallic surface of stainless steel not be covered with an opaque resin. In short, high surface quality and excellent corrosion resistance are more critical requirements with stainless steels than with other steel products.

However, it is difficult to obtain an adequate range of design options with only the simple metallic silver-gray color of the natural surface of stainless steel, even if various types of surface processing are applied. To overcome this drawback, products with broader designability have been developed, such as colored stainless steels electrochemically processed to form a thin oxide film or coated with a transparent resin so as to retain the original beauty and quality feeling of the material itself. Such surface treatment methods are also a means of satisfying the need for ever better corrosion resistance in stainless steel, because these surface treatments improve corrosion resistance.

In addition to the above-mentioned properties of corrosion resistance, beauty of surface, and designability, there is also a strong need to improve such other important qualities of steels as the strength, formability, weldability and quench-hardenability of martensitic stainless steels, and so on.

Further, it is a significant characteristic of stainless steel that it has an austenitic structure which does not

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exist in ordinary steel, so that many other functions are required of stainless steels in addition to rust-resistance and appearance; these are obtained by making use of the properties of latice structures such as austenite, ferrite, and martensite. For example, various types of stainless steels have been developed to obtain nonmagnetic properties, functionally gradient property, and multifunctionality.

This paper presents an outline of recent developments in the qualities, designability, and multifunctionality of stainless steel sheets.

2 Corrosion Resistance

For the practical use of stainless steels, it is necessary to consider all functional properties, not only corrosion resistance under a particular environment but also mechanical properties, weldability, and others. Although superior in general corrosion resistance, for example, austenitic stainless steels have a tendency toward 'stress corrosion cracking, especially in corrosive environments containing the Cl^- ion; this causes problems in their practical use in hot water vessels and chemical plants. On the other hand, ferritic stainless steels, though essentially immune to stress corrosion cracking and superior in other corrosion resistances when the Cr and Mo contents of the steels is increased, conversely suffer poor ductility in welded portions at higher Cr and Mo contents. Therefore, ferritic stainless steels have rarely been used as a structural material, in comparison with the commonly-used austenitic stainless steels.

The shortcoming of stainless steels described above have been overcome by extreme reduction of C and N contents in ferritic stainless steels and by high alloy contents in austenitic stainless steels.

2.1 Extreme Reduction of Carbon and Nitrogen

The ductility and toughness of ferritic stainless steels decrease with the increase of Cr content. It was made clear by Binder et al[1] that a reduction of C and N is extremely effective for the improvement of these properties. **Figure 1** shows the effect of C and N contents on the toughness of weld metals in a TIG weld of 16Cr ferritic stainless steel.[2] Toughness increases greatly as C and N contents decrease.

Kawasaki Steel Corp. has long made strenuous efforts to develop a relatively low cost steelmaking process for the extreme reduction of C and N, and has established the SS-VOD (Strongly stirred-vacuum oxygen decarburization) process,[3] a revolutionary steelmaking technology. This technology has made it possible to reduce C and N to extremely low levels, and has led the development of ferritic stainless steels with good ductility, toughness and corrosion resistance realized by increasing the Cr content and addition of other elements.[4]

Figure 2 shows the relationship between the measured pitting potential (in a 3.5 wt.% NaCl aqueous solution at 25°C) of 11 to 24%Cr ferritic stainless steels with extremely low C and N (100ppm, respectively) and the calculated value by Eq. (1), which was obtained by multiple-regression analysis of actual data on pitting potential. The calculated values of pitting potential have good coincidence with the measured results. Cr, Mo and Nb are effective elements to improve pitting corrosion resistance, but Cu causes slight deterioration.

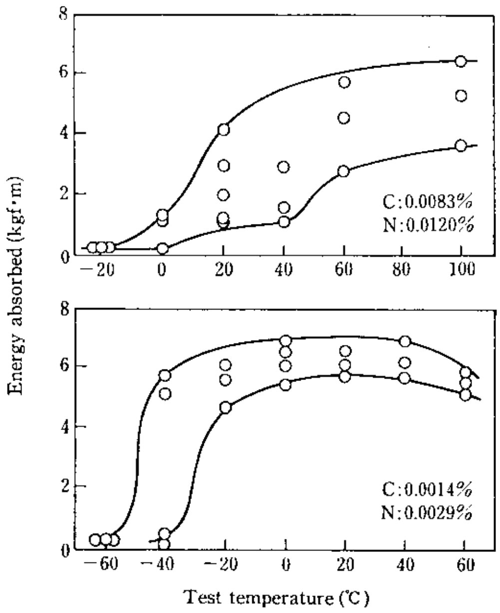

Fig. 1 Charpy energy vs temperature curves for TIG weld metals of 3 mm (0.12 in) thick sheet of 16% Cr steels

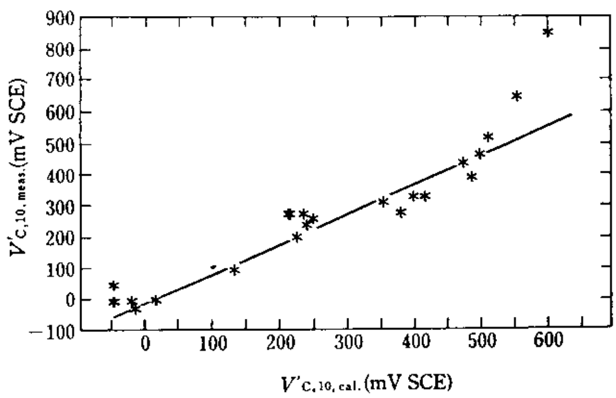

Fig. 2 Relationship between measured pitting potential $V'_{C,10,meas.}$ and calculated one $V'_{C,10,cal.}$

$$V'_{C,10}(\text{calculated}) = 29.16 \times (\%Cr) + 209.5(\%Mo) + 160.9(\%Nb) - 36.144(\%Cu) - 370.83 \quad \cdots (1)$$

Thus, many examinations on the effect of chemistry on not only pitting corrosion resistance but also crevice

Table 1 Pitting potentials ($V'_{C,10}$) and major applications of new ferritic stainless steels with low carbon and nitrogen contents

Steel	Composition Outline	$V'_{C,10}$ (mv SCE)	Major Applications
R 409L	11Cr-Ti-0.01C	105	Automobile exhaust pipe
SUS 430*	17Cr-0.06C	120	—
R 430LT	17Cr-Ti-0.02C	148	Bicycle rims
R 430LN	18Cr-Nb-0.02C	155	Bicycle rims
SUS 434*	17Cr-1Mo-0.06C	167	—
R 434LT1	18Cr-1Mo-Ti-0.003C	230	Warm water tanks
R 430LNM	18Cr-0.5Mo-Nb-0.02C	245	Warm water tanks
R 434LN1	18Cr-1Mo-Nb-0.003C	258	Warm water tanks
R 430CuN	19Cr-0.5Cu-0.5Nb-0.02C	286	Automobile external panel
R 434LT2	18Cr-2Mo-Ti-0.003C	370	Warm water tanks, Solar heat collector plates
R 434LN2	18Cr-2Mo-Nb-0.003C	388	Warm water tanks, Solar heat collector plates
R 445LY	22Cr-1Mo-Nb-Cu-0.02C	700	Roof
R 445M	22Cr-1Mo-Nb-0.02C	603	Automobile external panel
SR 26-1	26Cr-1Mo-Nb-0.003C		Warm water boilers
S 30-2	30Cr-2Mo-Nb-0.003C	>1 000	Plant for making organic acids
SR 26-4	26Cr-4Mo-Nb-0.003C		Plant for making organic acids
SUS 304*	18Cr-8Ni-0.06C	302	—
SUS 316L*	18Cr-12Ni-2Mo-0.02C	364	—

* Conventional stainless steels

corrosion resistance and atmospheric corrosion resistance have been carried out and have resulted in the development of many new ferritic stainless steels.

Table 1 shows pitting potentials ($V'_{C,10}$) and major applications of new ferritic stainless steels with low C and N contents, which are tradenamed "RIVER LITE" (hereinafter abbreviated R), in comparison with those of SUS 430 and SUS 304.

Major applications of R series steels are automobile exhaust devices (R409L), bicycle rims (R430LT and R430LN), material used in water environments, such as hot water vessels (R430LNM, R434LT1, R434LN1, R434LT2 and R434LN2), automobile external panels and trim (R430CuN and R445M), and uncoated roofs (R445LY). As high-chromium (above 25%) molybdenum-containing ferritic stainless steels, the production of which Kawasaki Steel has undertaken from Showa Denko K.K., SHOMAC30-2(S30-2) holds a record as the highest Cr and Mo containing steel; SHOMAC RIVER26-1(SR26-1) and SHOMAC RIVER26-4(SR26-4) have also been joint developed by Kawasaki Steel and Showa Denko K.K.[5] These steels are used in condenser tubes for electric generation plants, flue-gas desulfurization devices for pollution control units, heat exchangers for the diaphragm process of caustic soda production, and plants producing organic acids.

2.2 High Alloy Contents

In addition to Cr and Mo, N and Cu are useful in improving the corrosion resistance of stainless steel. It is well known that corrosion resistance improves in a chloride environment as the value of Cr(%) + (3~3.3) × Mo(%) increases.[6~8] **Figure 3** shows the difference in pitting corrosion resistance between ferritic and austenitic stainless steels containing 18 to 26%Cr and 0 to 4%Mo. Increased Cr and Mo contents improve

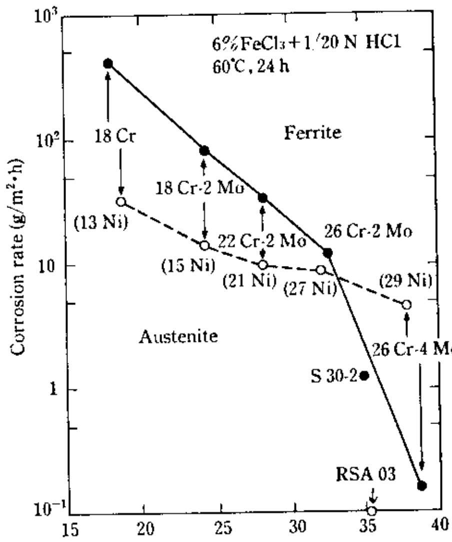

Fig. 3 Effects of Cr and Mo contents on pitting corrosion resistance of ferritic and austenitic stainless steels

pitting corrosion resistance, especially in ferritic stainless steels. An extra-low-C ferritic stainless steel containing 26%Cr and 4%Mo has corrosion resistance superior to that of austenitic stainless steel.[6,9,10] Recently, highly alloyed ferritic stainless steels were adopted for condenser tubes in many power stations in Europe and America,[11] because these stainless steels have excellent corrosion resistance.

One the other hand, it is possible to improve the corrosion resistance of austenitic stainless steel by adding N, because of the high solubility of this element. RSA03 in Fig. 3 is a sea-water resistant austenitic stainless steel (22Cr-17Ni-4.5Mo-0.3N) developed by Kawasaki Steel. Its pitting corrosion resistance is improved remarkably by increasing the N content.

It is well known that Cu improves the sulfuric acid corrosion resistance of stainless steel. In addition, recent studies have shown that Cu improves the chloride stress corrosion cracking resistance (SCC) of austenitic stainless steels in relatively mild conditions such as hot water environments.[12,13] **Figure 4** shows the stress corrosion resistance in lower concentrations of $MgCl_2$ solutions at each boiling point; the morphology of cracks in these cases is similar to that with hot water. Because stress corrosion resistance improves with increases in Cu content, Kawasaki Steel and other stainless makers have developed new austenitic stainless steels with excellent resistance of stress corrosion cracking by means of Cu addition.[13,14] Among other applications Kawasaki Steel's newly developed stainless steels will be adopted in hot water apparatuses. Unforeseen characteristics of conventional alloying elements are sometimes found in new environments, promoting the development of stainless steels.

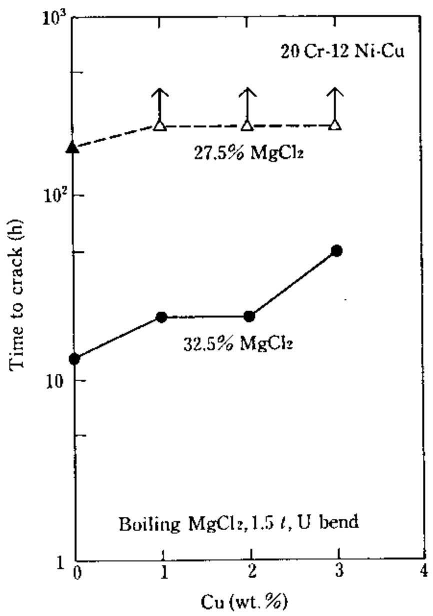

Fig. 4 Effect of Cu content on the susceptibility to stress corrosion cracking of 20Cr-12Ni stainless steel in boiling $MgCl_2$ solution by U bend method

3 Oxidation Resistance

Stainless steels are widely used not only in fields where corrosion resistance is required but also where oxidation resistance is required. Oxidation resistance is obtained by the formation of protective films on the surface of the stainless steel when exposed to high-temperature oxidizing atmospheres. Cr_2O_3, Al_2O_3 and SiO_2 are significant as protective films for the oxidation resistance. When higher quantities of Cr, Al and Si are contained in steels, better oxidation resistance is realized by preferential oxidation of such elements at the steel surface. Though beneficial for oxidation resistance, however, they may have a detrimental effect on other properties, such as press formability and ductility. To develop oxidation resistant stainless steels, alloying elements must be designed considering both beneficial and detrimental effects.

Increased Cr content inevitably entails increases in Ni content in austenitic stainless steels and results in higher material costs. Addition of a large amount of Al to Ni containing alloys causes embrittlement by promoting the precipitation of intermetallic compounds such as NiAl. Improvement of the oxidation resistance of austenitic stainless steels by Cr and Al addition has the adverse effects mentioned above, so that Si is the most widely applied alloying element.[15] On the other hand, Cr, Al, and Si are applied to ferritic stainless steels in which good formability and ductility can be maintained by balancing with other elements, especially interstitial C and N, and their stabilizing elements.

Figure 5 shows an example of the effect of Si on the

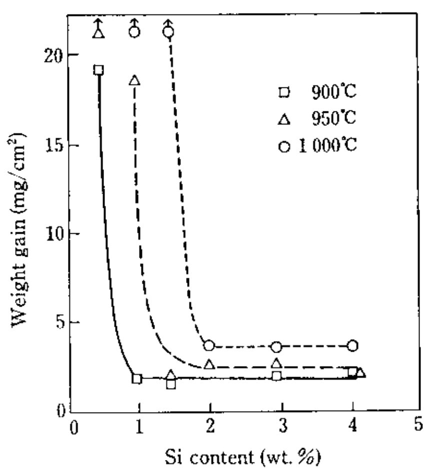

Fig. 5 Effect of Si content on weight change of 11%Cr-Ti steel by continuous heating in air at various temperatures for 300 h

oxidation resistance of ferritic stainless steel, developed as R409SR;[16] it is clear that the upper limit of service temperatures is raised as the Si content is increased. However, to maintain good press formability, the preferable content of Si is below 2%.

As good oxidation resistance is obtained by forming protective oxide films on the steel surface, in very thin steels such as foil, the amount of alloying elements which is sufficient for a thick sheet, can be inadequate in volumetric terms to form a film sufficient to protect the relatively large surface. This phenomena is discussed further in Sec. 6.2.

4 Quench Hardenability

Medium carbon martensitic stainless steels, represented by SUS420J1 and SUS420J2, have been applied to use in wear-resistant materials such as cutlery and tools. In order to obtain suitable hardness for a wear-resistant material, these conventional steels are subjected to heat treatment such as quenching and tempering, which involves cumbersome processing and higher costs. In addition to the shortcomings described above, tempering after quenching causes deterioration of corrosion resistance caused by the existence of a chromium depletion zone which results from the formation of chromium carbonitride.

R410DB, newly developed to solve this problem, is characterized by control of the (C + N) content of SUS410 in the range from 0.04% to 0.10% and by the addition of Mn to increase quenchability.[17]

The relation between hardness and quenching temperature in R410DB is shown in **Fig. 6** in comparison

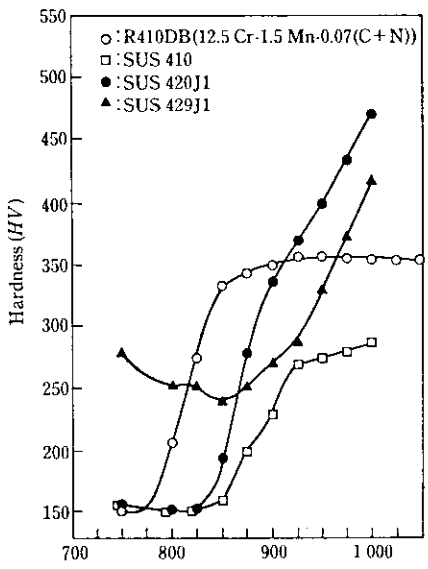

Fig. 6 Relationship between hardness and quenching temperature (Holding time, 10 min; cooling rate, 30°C/s)

with that of the conventional stainless steels. In medium carbon martensitic stainless steels such as SUS429J1 and SUS420J1, the effect of temperature on hardness is extremely great, so it is difficult to obtain the required hardness only by quenching, while the hardness of SUS410 is too low. In R410DB, on the other hand, the hardness of the quenched material is independent of quenching temperature. With this steel, which is mainly used for motor cycle brake disk, the constant hardness of 32 to 38HRC required for disks can easily be obtained by press-quenching alone after brief electromagnetic induction heating of about 5 to 20 s in a wide temperature range of from 930°C to 1100°C. R410DB has been also used as a wear-resistant material in concrete cutters and other applications, in addition to brake disks.

5 Development of Design-Quality Stainless Steels

The increase of demand for stainless steels is particularly conspicuous in the field of building materials. Technology for imparting designability to stainless steels has been developed in order to respond to the demand for higher grade and more diverse building materials. In contrast to conventional paint-coated steel sheets and colored aluminium goods, paint-coated stainless steel sheets were first used in roof materials. While this type of coated stainless steel is covered by an opaque paint and has only the one function of high corrosion resistance, stainless steels with high designability have been developed by methods such as a chemical coloring and transparent paint coloring to maintain the attractive metallic surface of stainless steel and thus take advantage of its surface appearance. The chemical coloring method is used with LUMINA COLOR, which is produced by an originally developed alternating current electrolyzing method. A transparent fluoric paint is used with Fancy Coat Color, which provides good atmospheric corrosion resistance.

5.1 LUMINA COLOR

The production method developed by INCO Co. for chemically colored stainless steel is well known, and consists of two solutions in which steels are soaked and a two-step process by which steels are colored and oxide films are then hardened.[18] The new production process researched and developed by Kawasaki Steel is a one-solution, one-step process using alternating current electrolyzing.[19]

The production method and the features of LUMINA COLOR are as follows:

(1) Alternating Current Electrolyzing

The schema of this new coloring method is shown in **Fig. 7**. Stainless steel stock for coloring and counterelectrodes are located in the coloring solution (for example, 450 g/l H_2SO_4 + 300 g/l CrO_3, 60°C). In the alternating current electrolyzing

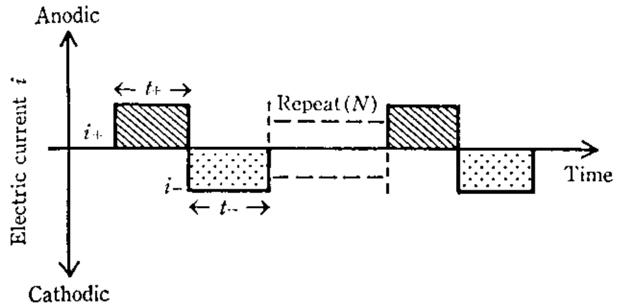

Fig. 7 Schema of alternating current electrolyzing for producing LUMINA COLOR

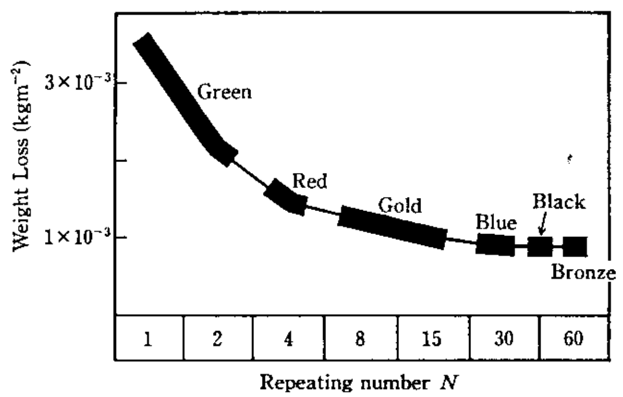

Fig. 8 Examples of coloring condition in alternating current electrolyzing for LUMINA COLOR ($i_+ = i_- = 10 A/m^{-2}$, total time 20 min, $t_+ = t_-$, 60°C)

method, periodic anodic and cathodic currents are applied for electrolysis over set time periods. Thus, the two processes of coloring and hardening proceed simultaneously in a one-solution bath.

(2) Color Control

Examples of coloring control for LUMINA COLOR are shown in **Fig. 8**. The conditions are as follows: anodic and cathodic electrolyzing currents, 10 A/dm^2; total electrolyzing period (unit electrolyzing time, $t_+ = t_-$), 20 min; repeat number, 1 to 60. The Y axis shows the weight loss of samples after coloring treatment. Bronze appears at $N = 60$. As this N number decreases (i.e. as unit electrolyzing time t_+, t_- becomes longer), black, blue, gold, red, green appear respectively. As shown in these examples, the color of the stainless steel is controlled by the combination of unit electrolyzing time (t_+, t_-) and repeat number (N) under the galvanostatic condition that anodic and cathodic electrolyzing current densities are in a steady state.

In the conventional method, bronze, blue, and gold appear, but black cannot be obtained with the same solution. For this reason another specific solution is needed for black.

(3) Color Clearness

The difference in color tone for gold stocks of SUS304 steel (hair line polished) with the conventional method and this new method is shown using the L, a, b values of the CIE color system.

	Lumina Color	Cvntl. meth.
L (dark: small ←L→ large: bright)	48-55	46-53
a (green: − ←a→ + : red)	0-4	2-7
b (blue: − ←b→ + : yellow)	22-30	15-21

The L value of LUMINA COLOR is two units higher, its a value is about three lower, and the average of b values is eight higher than that of the conventional colored stainless steels. This means that the color tone of LUMINA COLOR is brigher, yellower, and clearer than that of the conventional colored stainless steel.

(4) Corrosion Resistance

The corrosion rates of a gold LUMINA COLOR and conventional, and of an uncolored stock were measured weight loss after immersion for 2 h in a 30 wt.% $FeCl_3 \cdot 6H_2O$ solution at 30°C. The corrosion rate of LUMINA COLOR was 50 g/m^2·h, that of the conventional product was 80 g/m^2·h, while that of the uncolored material was 220 g/m^2·h. The corrosion resistance of LUMINA COLOR is thus the best among these three stocks.

The results of the analysis of surface films revealed that the Cr content of the surface layer of LUMINA COLOR was higher than that of the conventional colored product.

As LUMINA COLOR is superior in color clearness and corrosion resistance, as above mentioned, it is well suited for exterior panels in addition to interior panels, pipes, decorative materials, and other worked items.

5.2 Fancy-Coat-Color

Fancy-Coat-Color, developed by Kawasaki Steel, is a precoated stainless steel slightly colored with a fluoro resin paint. The paint provides superior weatherability, while its high transparency preserves the original appearance of the substrate. Although stainless steel has good corrosion resistance because of the passivation film formed on its surface, the disadvantages of this film in terms of not only paintability but also surface pretreatment to improve film adhesion have often been pointed out.

In addition to these common problems, surface pretreatment material is required to be sufficiently transparent to display the good appearance of the substrate after coating. Thus, a new type of fluoro-resin paint with good adhesion to stainless steel and excellent transparency is also necessary to assure high film performance.

Table 2 Specifications of substrate

Types of steel	SUS 304, SUS 430
Available size	
Thickness	0.3~1.5 mm
Width	≤1 219 mm
Length	≤4 000 mm
Finishes	Hair-line polishing, etching, etc

Kawasaki Steel and Toa Paint Co. Ltd. undertook joint development of Fancy-Coat-Color. Based on this work, LUMIFLON (Asahi Glass Co.) was adopted as the base fluorinated resin for a paint which is characterized by superior gloss and high solvent-solubility. The types of hardener, ultraviolet absorbent, and pigments and their contents were determined carefully to ensure good formability and adhesion of the coated film without degradation of the superior performance of the base resin. On the material side, a surface pretreatment method was also developed to improve paint adhesion without degrading the surface properties (corrosion resistance, high metallic luster) of the stainless steel.

Tables 2 and 3 show the specifications and properties of Fancy-Coat-Color, revealing its superiority in paint adhesion properties. Formability is especially high, and is sufficient to withstand the severe bending characteristic of building materials applications.

For these reasons, Fancy-Coat-Color is expected to find a wide range of uses, such as architectures, household appliances, and others, in addition to building material.

6 Development of Multifunctional Steels

The development in a variety of applications fields of steel products which untilize the multifunctional properties of stainless steels is noteworthy, and indicates that stainless steels have a wide range of desirable features. This suggests expanding future applications for stainless steels. In this section, three steels newly developed as functional materials are described.

6.1 Material for Far-infrared Radiators

Water and organic compounds have high absorption characteristics for radiation over the 3 μm wavelength, which is called far-infrared. Radiation heating used for materials in this wavelength range can save energy and provide high productivity because of their high absorption efficiency. Recently, far-infrared radiation heating has been applied increasingly[20] in paint-drying and the food industry.

Because it is well known that metal oxides (i.e. Cr_2O_3, Al_2O_3, SiO_2, TiO_2, etc.) have high efficiency in far-infrared radiation, these oxides are hot sprayed or painted with resin on a stainless steel substrate to form heating elements. However, problems of durability are caused by spalling of the surface coatings after cyclic heating and rusting of the substrate by vapor condensates.

Incidentally, the oxides mentioned above are well-known as oxide films formed on stainless steel surface after exposure at high temperature in a proper atmosphere, and firmly bond to the substrate, resulting in a functionally gradient material[21]. Usually, a Cr depleted zone is formed in stainless steel under the oxide film which grows on the surface and this causes degradation of the corrosion resistance of the steel. To overcome the

Table 3 Properties of Fancy-Coat-Color

Items of Test	Result	Test Method
Color	4 types	clear, gray, bronze, gold
Film thickness	20 μm	
Pencile hardness	F/2H	"Mitsubishi Uni"
Paint adhesion	Excellent	Cross-cut adhesion Erichsen test: 6 mm
Formability	Excellent	Bending test 1*T* 180°
Durability*1	Excellent	Boiling water for 2 h
Humidity resistance	Excellent	95%RH, 50°C*1 000 h
Salt spray test	Excellent	5%NaCl, 35°C*500 h
Acid resistance	No change	5%H_2SO_4, 20°C*168 h
Alkali resistance	No change	5%NaOH, 20°C*168 h
Acc. weathering test		Sunshine type W-O-M
Adhesion	100/100	3 000 h
Gloss retension	95%	
Discoloring and fading (ΔE)	2.1	

*1 90° bent area of test pannel

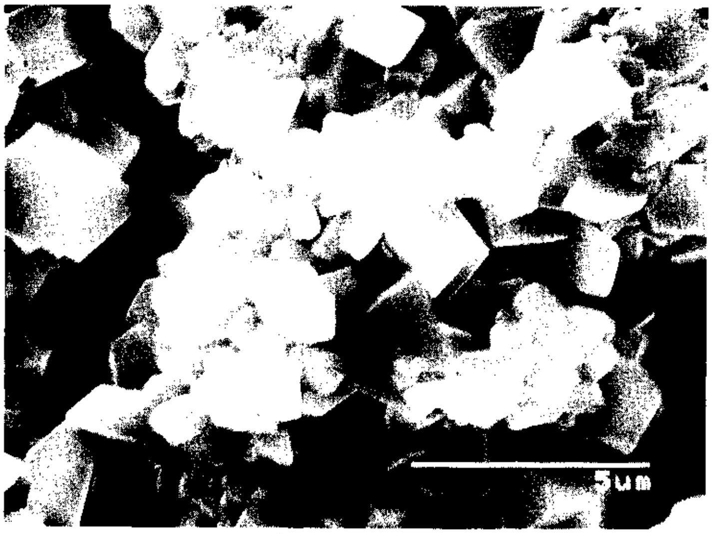

Photo 1 Cr_2O_3 on the surface of RF-100 sheet

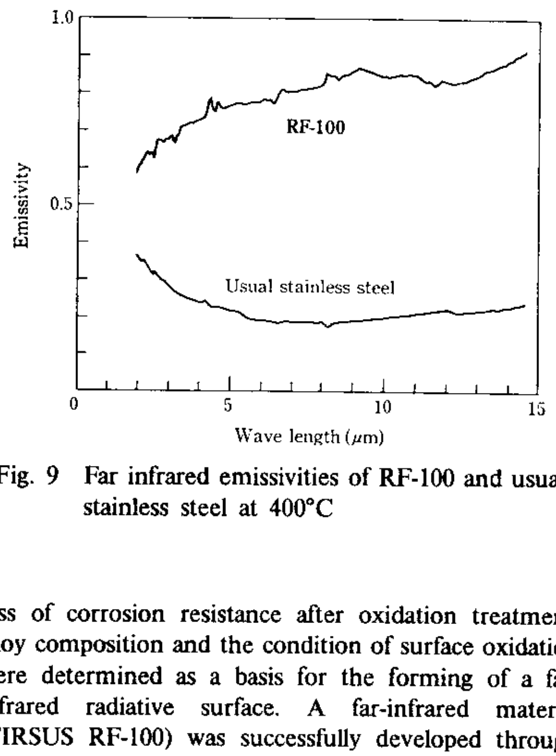

Fig. 9 Far infrared emissivities of RF-100 and usual stainless steel at 400°C

loss of corrosion resistance after oxidation treatment, alloy composition and the condition of surface oxidation were determined as a basis for the forming of a far-infrared radiative surface. A far-infrared material (FIRSUS RF-100) was successfully developed through co-research with Osaka Gas Co. Ltd., and has an almost pure Cr_2O_3 covering on its surface as shown in **Photo 1**. As shown in **Fig. 9**, the emissivity of far-infrared radiation of FIRSUS RF-100 is more than 0.8. In contrast, that of non-treated conventional stainless steel is about 0.2. RF-100 also shows superior corrosion resistance after a salt spray test over 700 h and good thermal shock resistance to spalling of the Cr_2O_3 film from the substrate after quenching from 700°C. Based on its performance, RF-100 has been applied to several gas-burning dryer systems with good results.

6.2 Substrate Material for Catalytic Converters

For automobile emmission control systems, ceramics honeycomb-structure monolith has been used as a catalyst substrate. However, the wall thickness of the monolith is rather thick, more than 150 μm, causing high engine back pressure resulting from resistance to the exhaust gas flow. If the wall thickness were reduced to around 50 μm, it was expected that engine performance would be improved. There was substantial demand for thin foils for the monolith, which would also have good oxidation resistance under severe cyclic-heating conditions.

Among the oxidation resistant steels, Fe-Cr-Al alloy was first proposed because of its good productivity and properties. But the 18Cr-3Al steel used for conventional combustion devices or the even higher Al-content 20Cr-5Al steel was unable to pass the oxidation test at 1150°C for 100 h when reduced in thickness to a 50-μm foil. High Al-containing steels form a protective Al_2O_3 film, as described in Sec. 3, but when the thickness of the steel is reduced to that of a thin foil, the Al content is in volume terms insufficient to form an Al_2O_3 film covering substantially the entire surface. This being the case, Cr and Fe are rapidly oxidized after the Al is consumed. Greater addition of Al and Cr improve oxidation resistance, but the toughness of the alloy is lowered to a point where processing by commercial production facilities is not possible.

Besides Cr and Al, it is well known that rare earth metals improve oxidation resistance. They especially improve oxidation resistance by preventing the oxide film from spalling and are widely added to electric heater materials. Rare earth metals are usually used as "Mischmetall", in which La and Ce are considered to

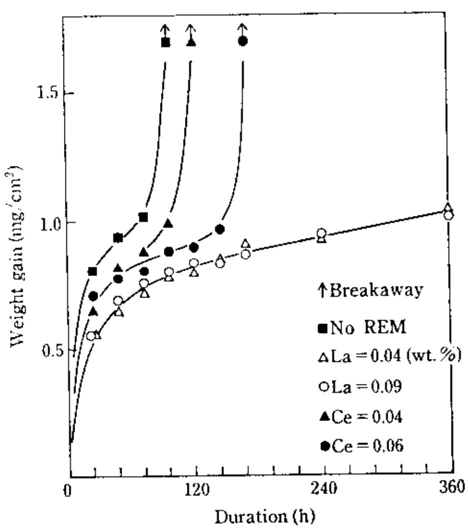

Fig. 10 Effects of REM contents on the oxidation resistance of Fe-20Cr-5Al foil 50 μm thick at 1150°C in air

have the same effects. According to detailed study, however, La is more effective than Ce in improving oxidation resistance, as shown in **Fig. 10**. Although Ce-containing foil suffers breakaway oxidation after a short time, La-containing foil maintains good oxidation resistance for a long period after complete consumption of Al. The effect of La is to promote formation of a Cr_2O_3 layer under the Al_2O_3 surface film. This Cr_2O_3 layer is thought to protect Fe from oxidization and thus prevent breakaway oxidation[22].

Using the results mentioned above, a super-oxidation resistant steel R20-5SR[23] was developed, and a 50-μm foil of R20-5SR is now in use in the catalytic converters of new passenger cars[24]. As this steel has excellent oxidation resistance, not only foil but ordinary thickness sheet are expected to be applied to various types of industrial and household combustion equipment.

6.3 Nonmagnetic Steel

For guide-rollers of video cassettes and magnetic sleeve tubes of copying machines, steels with good nonmagnetizability and wear resistance are required. Usually, SUS316 is used as the material for such tubes. These welded tubes are heat treated to eliminate delta ferrite (magnetic phase) and then cold drawn to obtain wear resistance. SUS316, developed as a material for corrosion resistance, contains considerable amounts of Ni and Mo, which also cause good stability of the austenite phase. This steel is frequently used as a nonmagnetic material, but contains an extremely large amount of Mo which serves only the purpose of ensuring nonmagnetic properties. Although this Mo content is not necessarily detrimental from the viewpoint of function, it increases the cost of the material significantly. The optimum composition for nonmagnetic steel tubes was therefore studied.

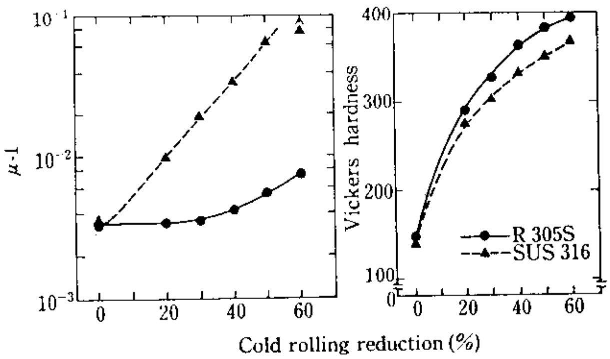

Fig. 11 Changes in permeability and Vickers hardness of R305S and SUS 316 with cold rolling reduction

The major points in the study of chemical composition were as follows: First, to minimize the transformation of strain-induced martensite from the austenite phase during cold work; second, to ensure the delta-ferrite phase is not present in the weld area; and third, to avoid weld defects such as undercut at weldments. Satisfactory results were obtained with a newly developed R305S of a 20Cr-13Ni-0.9Mn composition[25].

As shown in **Fig. 11**, R305S is a steel with a very stable austenite phase, which means that even if it is cold-rolled at a reduction of about 60%, it retains its superior nonmagnetizability. Thus, it can be hardened sufficiently by cold working to obtain good wear resistance. The magnetic permeabilities of R305S and SUS316 are 1.0040 and 1.0230 for weld areas and 1.0033 and 1.0034 for base metals, meaning that heat treatment for delta-ferrite elimination is not needed with R305S weld tubes. One of the significant features of R305S is its low content of Mn compared to conventional nonmagnetic steels, with result that the steel is generally free from weld defects such as undercut, reducing the need for bead conditioning before cold drawing.

7 Conclusions

Recent developments in the quality, designability and multi-functionality of stainless steel sheets at Kawasaki Steel are summarized as follows:

(1) For improvement of corrosion resistance:
   (a) Many new ferritic stainless steels with excellent corrosion resistance have been developed by taking measures to obtain extra-lower carbon content, while improving general properties.
   (b) By raising the contents of alloying elements, various stainless steels have been developed using Cr, Mo, N or Cu element.

(2) For the improvement of oxidation resistance, a ferritic stainless steel was developed by increasing the content of Si.
(3) To improve quench-hardenability, a martensitic stainless steel was developed by controlling C, N and Mn contents; this steel possesses stable quality after only quenching and does not require temper annealig.
(4) To impart broader design qualities to stainless steel while making use of its attractive metal surface, the following colored products were developed:
  (a) Colored stainless steels with a transparent thin oxidation film formed by an alternating-current electrolyzing method.
  (b) Colored stainless steels with a transparent fluororesin film, which has excellent adhesion to the steel surface and provides both superior resistance to atmospheric corrosion and good formability.
(5) To impart multi-functionality to stainless steels, mainly as stainless steel with ceramic properties, the following products were developed:
  (a) As a far-infrared radiator material, high Cr stainless steel with a thick Cr-oxide film was developed by heart-treatment; this steel has superior corrosion resistance and excellent durability.
  (b) As a catalyst substrate for use in automobile exhaust systems, a stainless steel foil with superior high-temperature corrosion resistance was developed as an alternative to ceramics.
  (c) As for other functions, a nonmagnetic stainless steel has also been developed.

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