NIPPON STEEL TECHNICAL REPORT No. 71 OCTOBER 1996

UDC669.14.018.8-194.56:620.194

Development of Austenitic Stainless Steels YUS 110M and YUS 27A-M with Stress Corrosion Cracking Resistance

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Abstract:

Two austenitic stainless steels have been newly developed by using silicon and copper. These stainless steels are for appliances that need formability and stress corrosion cracking (SCC) resistance. One steel is YUS 110M (18Cr-10Ni-2Si-2Cu-0.7Mo) which has formability comparable to that of SUS 304, pitting corrosion resistance equivalent to that of SUS 316, and excellent SCC resistance. The other steel is YUS 27A-M (17Cr-7Ni-1.5Si-2Cu), which features SCC resistance higher than that of YUS 27A for use in appliances that require deeper drawability and stretchability than is provided by SUS 304. The effects of silicon and other alloying elements on SCC resistance and formability and the properties of the new ferritic stainless steels are described.

1. Introduction

SUS 304 has excellent weldability and formability, but has suffered SCC originating in crevice corrosion in neutral chloride environments, such as heated tap water. For example, electric calorifiers are made of SUS 444 (called YUS 190 at Nippon Steel).

Nippon Steel formerly had YUS 110 (16Cr-13Ni-4Si-1Cu) as a grade with its SCC resistance improved by using of the formability of austenitic stainless steels. YUS 110 was difficult to manufacture, however, because of the need for sharply reducing the molybdenum and phosphorus contents to obtain desired SCC resistance. In recent years, formability has received increasing attention through improvements in the performance of hot-water supply equipment and similar appliances. Nippon Steel has developed two new austenitic stainless steels to meet the demand.

One is called YUS 110M, an austenitic stainless steel that has formability comparable to that of SUS 304 for hot-water supply equipment, pitting corrosion resistance and crevice corrosion resistance equivalent to those of SUS 316, and SCC resistance to 130°C in an environment containing 200 ppm of Cl^- ions, which is the maximum permissible Cl^- ion concentration for tap water. The other is designated YUS 27A-M, an austenitic stainless steel that excels in deep drawability and stretchability and has

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improved SCC resistance to magnesium chloride solutions while maintaining the formability of YUS 27A (17Cr-7Ni-2Cu), which is used for kitchen sinks and gas burners, among other things.

2. Development of YUS 110M

The chemical composition of YUS 110M was designed by making use of findings about its effects on hot workability as well as corrosion resistance and formability. Silicon and copper are effective especially for SCC resistance, as observed with YUS 110 and various other stainless steels developed for water heaters[1-4]. The conventional austenitic stainless steels containing these elements, SUS 304 whose formability is aimed at, and SUS 316 whose pitting corrosion resistance and crevice corrosion resistance are aimed at, were studied as comparative materials.

2.1 Experimental methods

Eight austenitic stainless steels containing silicon or copper, including SUS 304 and SUS 316, were used for the experimental study. The chemical compositions of cold-rolled sheets about one mm in thick are listed in **Table 1**.

Data arranged by the contents of alloying elements were used for the properties other than SCC resistance, and the relative ranks of the experimental steels were understood accordingly. SCC resistance was evaluated with a solution in which 200 ppm of Cl^- ions, the maximum permissible Cl^- ion concentration for tap water, was adjusted with sodium chloride (NaCl). Specimens were spot-welded specimens considered effective in evaluating SCC resistance[5]. A 15-mm square blank was placed on a 30-mm square blank and spot welded at the center. The specimens produced were thus subjected to stresses from the crevices formed and the spot welds made. The specimens were immersed in a solution held at intervals of 20°C between 50°C and 150°C for seven days. A glass container fitted with a cooling tube for preventing evaporation was used up to 90°C, and a titanium autoclave was used at 110°C and above. The solution volume per unit surface area was 30 mL/cm^2, and two specimens were tested at a time. After the test was completed, the specimens were drilled at the spot welds, and the crevices were opened and observed under a microscope at a magnification of 100-500 times.

2.2 Experimental results

2.2.1 SCC resistance

The test results of SCC resistance in the 200 ppm Cl^- ion solution at 50°C to 150°C are shown in **Fig. 1**.

The critical temperature is about 50°C for SUS 304 and about 90°C for SUS 316. The critical temperature is 100°C to 110°C for the steels A, B, and D that have approximately the same chromium and nickel contents as SUS 304 and contain 2% to 3% Cu. This means that the steels A, B, and D exhibited SCC resistance about 50°C higher than that of SUS 304. Comparison of the steels A and B suggests that the SCC resistance is slightly reduced by the addition of 1%Mo.

The silicon-bearing steels C (3.8Si-1Cu) and E (3.5Si-0.7Cu), each containing about 1%Cu, rose in the critical temperature by about 20°C compared with the steels A, B, and D, partly because of their high nickel content. The steel F (24Cr-14Ni-2Si-0.8Mo) has a critical temperature above the target temperature of 130°C, but its formability is poor as described later. In either case, silicon and copper are effective for SCC resistance in neutral chloride environments, particularly when they are added in combination.

2.2.2 Crevice corrosion resistance

Fig. 2 shows the relationship between the crevice corrosion test results and pitting index (PI) of base metal specimens in a 4.9% NaCl solution at pH 2 and 70°C[6]. A 30-mm square blank and a 20-mm square blank were assembled with polycarbonate bolts and nuts to form a base-metal specimen with crevices. The corrosion rate is arranged by the PI (Cr + 0.5Ni + 3Mo + 2Cu + 20N). The PI must be 29 or more to obtain crevice corrosion resistance equal or superior to that of SUS 316. The circled numerals in **Fig. 2** refer to the numbers of the steels listed in **Table 1** and indicate the relative ranking of the steels in terms of crevice corrosion resistance.

2.2.3 Formability

The formability of the stainless steels is shown in **Fig. 3**[7], which shows the relationship between ΔNi (%) [$Ni + Cu + 0.5Mn + 35(C + N) - (Cr + 1.5Mo - 20)^2/12 - 15$][8] and the elongation determined in a tension test. The ΔNi value of about 2% or less is desirable to achieve formability comparable to that of SUS 304.

2.2.4 Hot workability

Concerning manufacturability, the relationship between the hot-cracking tendency and δ ferrite content of the eight steels is shown in **Fig. 4**[7]. To obtain desirable hot workability, the δ ferrite content [$3(Cr + Mo) + 4.5Si - 2.8Ni - 1.4(Mn + Cu) - 84(C + N) - 19.8$] should be 5% or less.

2.3 Properties of YUS 110M

These test results were summarized to establish the base composition 18%Cr-2%Si-2%Cu. The typical chemical composition of YUS 110M is given in **Table 2**.

2.3.1 SCC resistance

The SCC test results of spot-welded specimens in the same 200 ppm Cl^- ion solution as described are shown in **Fig. 5**. The critical temperature of YUS 110M is above the target of 130°C.

Table 1 Chemical compositions of stainless steels (mass%)

No.	Steel	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	N
1	SUS 304	0.052	0.57	0.91	0.029	0.004	9.11	17.95	0.13	0.13	0.017
2	SUS 316	0.042	0.57	0.82	0.025	0.001	12.25	17.26	2.07	0.28	0.027
3	A	0.040	0.66	1.09	0.029	0.004	6.43	17.48	0.15	2.21	0.056
4	B	0.050	0.72	1.02	0.025	0.008	6.89	17.62	1.01	2.08	0.040
5	C	0.051	3.79	0.56	0.015	0.002	12.52	16.32	0.005	1.10	0.031
6	D	0.024	0.28	0.68	0.029	0.001	9.26	18.10	0.20	3.30	0.023
7	E	0.060	3.49	0.26	0.018	0.003	13.35	19.30	0.20	0.74	0.052
8	F	0.09	1.95	1.59	0.025	0.004	13.60	24.20	0.75	0.20	0.251

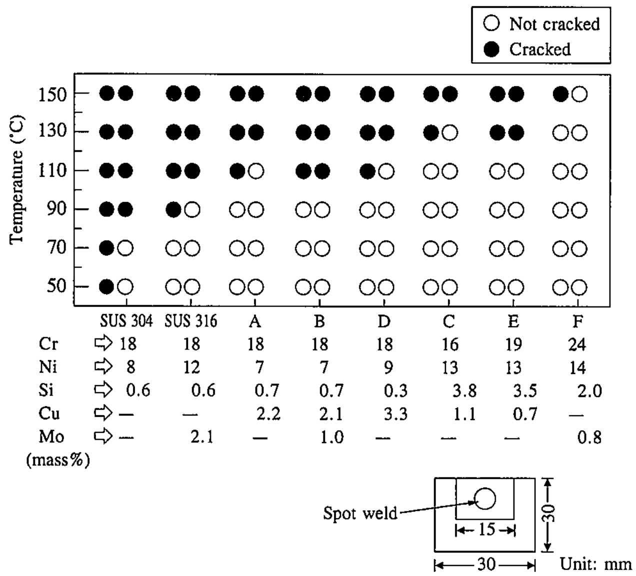

Fig. 1 SCC test results of spot-welded specimens (200 ppm Cl⁻ ion solution, seven days)

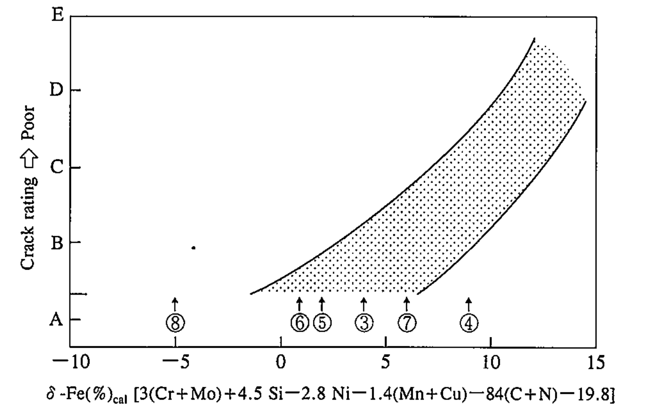

Fig. 4 Ranking of stainless steels by relationship between δ ferrite content and hot crack rating

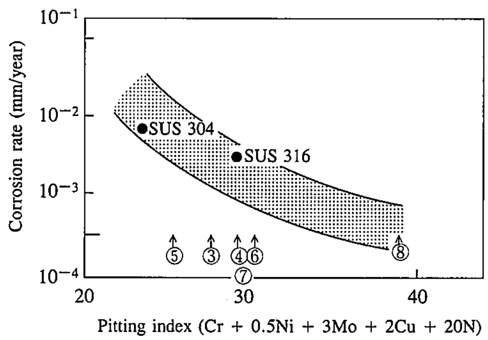

Fig. 2 Stainless steels ranked by crevice corrosion resistance (4.9% NaCl solution, 70°C, 3,000 hours)

Table 2 Chemical composition of YUS 110M (mass%)

C	Si	Mn	P	S	Ni	Cr	Mo	Cu
0.050	1.90	0.61	0.020	0.001	10.25	17.70	0.79	2.02

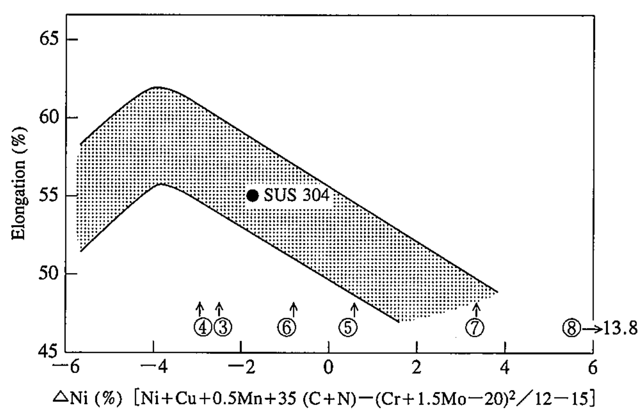

Fig. 3 Ranking of stainless steels by relationship between ΔNi and elongation

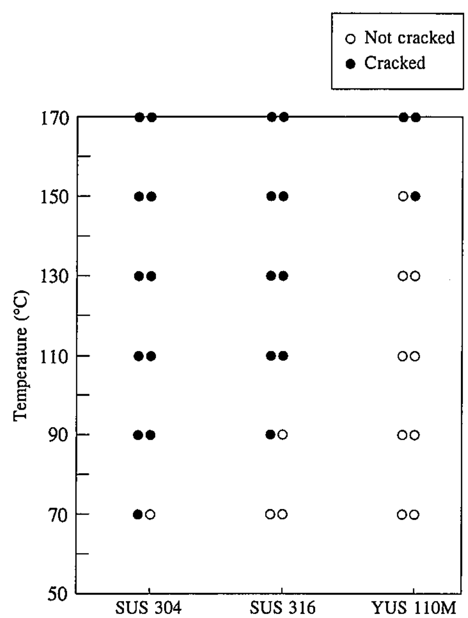

Fig. 5 SCC resistance of YUS 110M (spot-weld crevice, 200 ppm Cl⁻ ion solution, seven days)

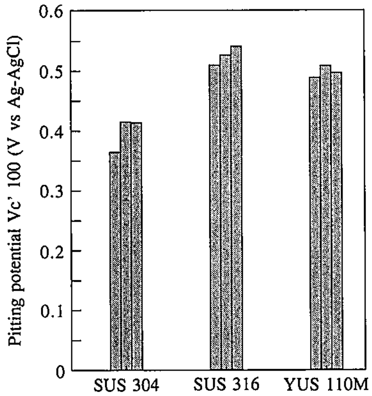

Fig. 6 Pitting corrosion resistance of YUS 110M (base-metal, 200 ppm Cl^- ion solution, 85°C)

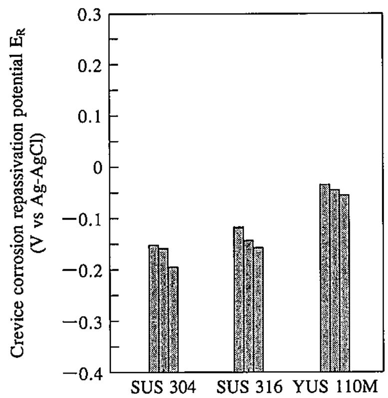

Fig. 7 Crevice corrosion resistance of YUS 110M (base metal crevice, 200 ppm Cl^- ion solution, 85°C)

Table 3 Mechanical properties of YUS 110M

Property	Direction	YUS 110M	Reference	
			SUS 304	SUS 316
0.2% offset yield strength (N/mm^2)	L	320	300	300
	V	310	290	300
	T	310	290	290
Tensile strength (N/mm^2)	L	640	680	620
	V	610	630	600
	T	610	640	600
Elongation (%)	L	47	50	46
	V	51	54	51
	T	51	55	50

JIS No. 13B specimens
Specimen orientation
L: Parallel with rolling direction, V: 45° to rolling direction, T: 90° to rolling direction

Table 4 Formability properties of YUS 110M

Property	Direction	YUS 110M	Reference	
			SUS 304	SUS 316
Strain hardening coefficient (n value)	—	0.38	0.40	0.80
Plastic strain ratio (r value)	L	0.85	0.90	0.80
	V	1.10	1.13	1.10
	T	0.79	0.83	0.95
	$\bar{x}$	0.95	1.00	0.99
Limiting draw ratio (LDR)	—	2.06	2.06	2.06
Bulge forming height (mm)	—	40.0	43.5	40.4
Erichsen value (mm)	—	Base metal 12.0	13.6	12.4
	—	Weld metal 11.9	—	—

Note 1) Limiting draw ratio: Specimen shape: 80-97.5 mm ϕ, Punch: 40 mm ϕ, Die: 43 mm ϕ, Blankholder force: 1 ton, Lubricant: Johnson Wax #122
Note 2) Bulge forming: Specimen shape: 160-mm hexagon, Round die: 100 mm ϕ, Profile radius: 4 mm, Blankholder force: 37 tons
Note 3) Erichsen value: Measured by Erichsen test method A specified in JIS Z 2247

2.3.2 Pitting corrosion resistance and crevice corrosion resistance

The pitting potential of three steels measured in the 200 ppm Cl^- ion solution at 85°C are shown in **Fig. 6**. The repassivation potential E_R of crevice corrosion test specimens having crevices formed with polycarbonate bolts and nuts are shown in **Fig. 7**. YUS 110M has pitting corrosion resistance comparable to that of SUS 316 and crevice corrosion resistance superior to that of SUS 316.

2.3.3 Formability

Tables 3 and **4** list the mechanical properties and formability of YUS 110M in comparison with SUS 304 and SUS 316, respectively. YUS 110M has mechanical properties and formability comparable to those of SUS 304.

3. Development of YUS 27A-M

The quality targets of YUS 27A-M are formability comparable to that of YUS 27A and SCC resistance equivalent to that of high-nickel SUS 304 in a magnesium chloride ($MgCl_2$) solution. Because elongation decreases as ΔNi increases in the range of −4 to +4 as noted above, ΔNi was set at about −4 on the basis of YUS 27A, and the alloying elements, such as carbon, nitrogen, silicon, chromium, nickel, molybdenum, and copper, were investigated for the effects they may have on SCC resistance.

3.1 Experimental methods

The experimental materials were one-mm thick cold-rolled sheets of 10 austenitic stainless steels with their carbon, nitrogen, silicon, copper, nickel, and molybdenum contents changed by vacuum melting. The chemical compositions of these stainless steels, including YUS 27A and high-nickel SUS 304, are listed in **Table 5**.

To evaluate SCC resistance as described in JIS (Japanese Industrial Standard) G 0576, specimens were loaded under a constant stress of 15 kgf/mm^2 or 20 kgf/mm^2 in a boiling 42% $MgCl_2$ solution, and the time to their failure was measured. Ring bead specimens, each having a 30-mm diameter blank TIG (tungsten inert gas) welded to a 50-mm square blank, were immersed in the boiling 42% $MgCl_2$ solution for 16 hours or 24 hours, and their degree of cracking was evaluated by a liquid penetrant test. To evaluate pitting corrosion resistance, TIG-welded specimens were

Table 5 Chemical compositions of stainless steels (mass%)

Steel	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	N
SUS 304	0.046	0.45	0.82	0.026	0.0070	9.03	18.07	0.13	0.19	0.041
YUS 27A	0.042	0.69	1.13	0.027	0.0004	6.60	17.43	0.21	2.34	0.058
A	0.039	0.71	0.83	0.025	0.0004	8.14	17.63	0.19	1.50	0.028
B	0.039	0.71	0.83	0.025	0.0004	8.15	17.63	0.18	2.33	0.028
C	0.044	0.98	1.14	0.026	0.0003	6.60	17.40	0.21	2.34	0.058
D	0.044	1.51	1.14	0.025	0.0004	6.54	17.47	0.20	2.33	0.055
E	0.040	1.50	1.14	0.025	0.0004	6.53	17.47	0.53	2.31	0.053
F	0.040	1.50	1.13	0.025	0.0004	6.54	17.48	1.04	2.34	0.056
G	0.021	0.70	1.10	0.026	0.0040	8.87	17.35	0.18	2.32	0.010
H	0.021	1.50	1.10	0.026	0.0040	8.88	17.35	0.18	2.32	0.010

immersed in a 2% ferric chloride ($FeCl_3$) solution at 50°C for 168 hours, and the depth of the resultant pits was measured. The pitting potential of the specimens was also measured in a 3.5% sodium chloride (NaCl) solution at 30°C as specified in JIS G 0577. The formability of the stainless steels was evaluated by the Erichsen test method B prescribed in JIS Z 2247.

3.2 Experimental results

3.2.1 SCC resistance

The relationship between the applied stress ratio (applied stress/0.2% offset yield strength ratio) and the time to failure by SCC in the boiling 42% $MgCl_2$ solution is shown in **Fig. 8**.

The time to failure is equivalent to that of YUS 27A when 1.0%Si is added. The addition of 1.5%Si improves the time to failure to the same level as that of high-nickel SUS 304. The addition of 0.5%Mo or 1.0%Mo to 1.5%Si has no effect on the time to failure. The increase in the nickel content improves the SCC resistance. To obtain SCC resistance equal or superior to that of high-nickel SUS 304, it is necessary to reduce the carbon and nitrogen content. The addition of silicon significantly improved the SCC resistance of the high-nickel steels.

The SCC resistance test results of TIG-welded ring bead specimens in the boiling 42% $MgCl_2$ solution at 50°C are shown in **Fig. 9**. The susceptibility to SCC was similar to that of high-nickel SUS 304 when 1.5%Si and molybdenum were added. The SCC susceptibility of the high-nickel and low-carbon steels and the nitrogen steels was lower than that of high-nickel SUS 304.

3.2.2 Pitting corrosion resistance

The results of the immersion test in the 2% $FeCl_3$ solution at 50°C and the results of the pitting potential test in the 3.5% NaCl solution at 30°C are shown in **Figs. 10** and **11**, respectively.

In both tests, the pitting corrosion resistance was improved by the addition of silicon singly or in combination with molybdenum.

The high-nickel and low-carbon steels and the nitrogen steels had lower pitting potential than YUS 27A and poorer pitting corrosion resistance.

3.2.3 Formability

The Erichsen values of the stainless steels measured by the Erichsen test method B described in JIS Z 2247 are shown in **Fig. 12**.

The addition of up to 1.5%Si provided an Erichsen value equivalent to that of YUS 27A, and the addition of molybdenum reduced formability. The high-nickel and low-carbon steels and the nitrogen steels were similar in formability to high-nickel SUS 304 without a copper addition.

3.3 Properties of YUS 27A-M

Given the above results and the change in phase balance with

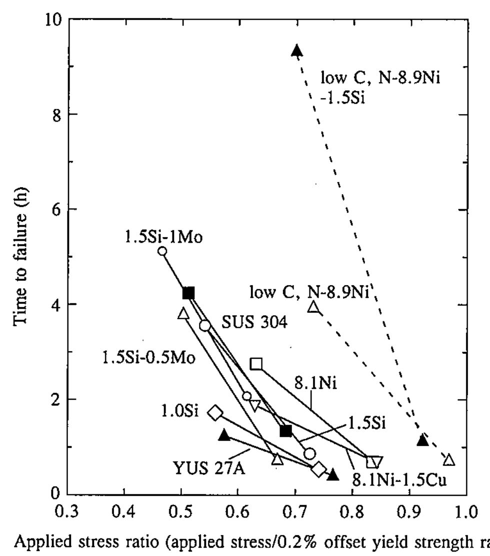

Fig. 8 Relationship between applied stress ratio and time to failure by SCC

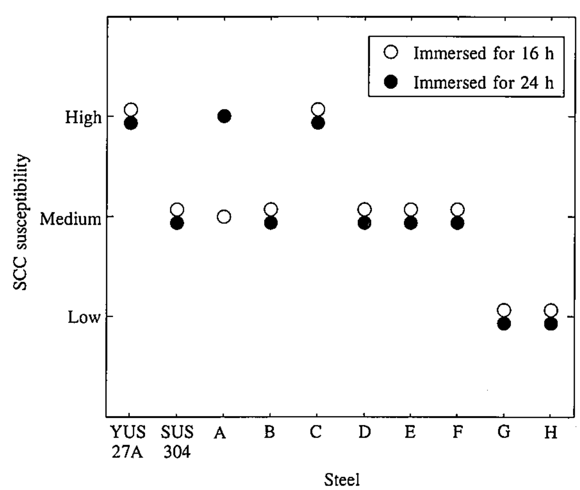

Fig. 9 SCC susceptibility of TIG-welded specimens

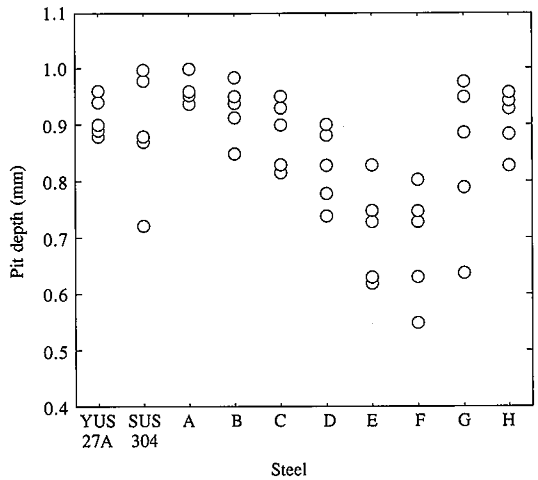

Fig. 10 Pit depth of TIG-welded specimens

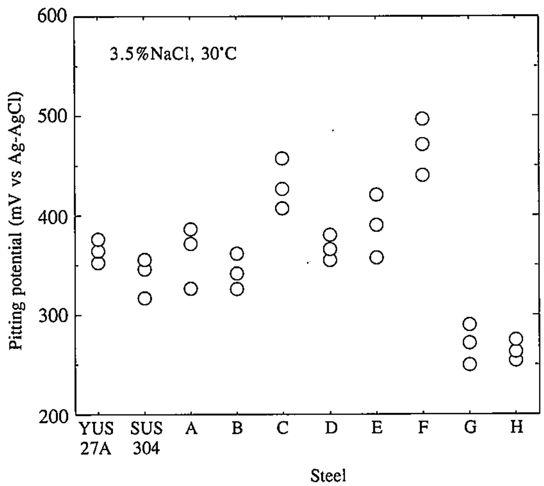

Fig. 11 Pitting potential of TIG-welded specimens

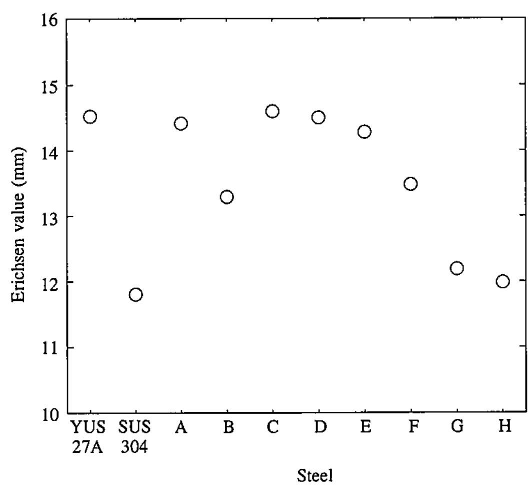

Fig. 12 Erichsen value measured by Erichsen test method B

the addition of silicon, the chemical composition of YUS 27A-M was set at 17Cr-7Ni-1.5Si-2Cu by decreasing the chromium content and increasing the nitrogen content as compared with YUS 27A. The typical chemical composition of YUS 27A-M is shown in **Table 6**.

3.3.1 SCC resistance

The relationship between the time to failure in the boiling 42% $MgCl_2$ solution and elongation is shown in **Fig. 13**. YUS 27A-M has elongation comparable to that of YUS 27A and SCC resistance equal or superior to that of high-nickel SUS 304. Three TIG-welded ring bead specimens after the immersion test in the boiling 42% $MgCl_2$ solution are shown in **Photo 1**. YUS 27A and high-nickel SUS 304 cracked, but YUS 27A-M did not crack.

3.3.2 Formability

The mechanical properties and formability of YUS 27A-M are shown in comparison with those of YUS 27A and high-nickel SUS 304 in **Table 7** and **Fig. 14**, respectively. YUS 27A-M is superior to high-nickel SUS 304 and equivalent to YUS 27A in mechanical properties and formability.

Table 6 Chemical composition of YUS 27A-M (mass%)

	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	N
Representative value	0.05	1.50	1.06	0.016	0.002	7.00	17.11	0.10	2.30	0.06

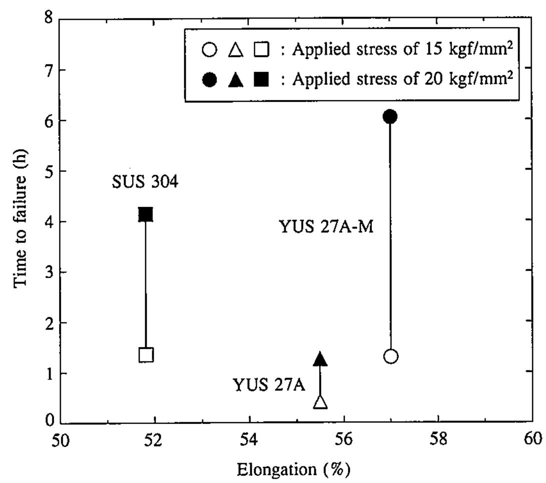

Fig. 13 Relationship between time to failure and elongation of YUS 27A-M

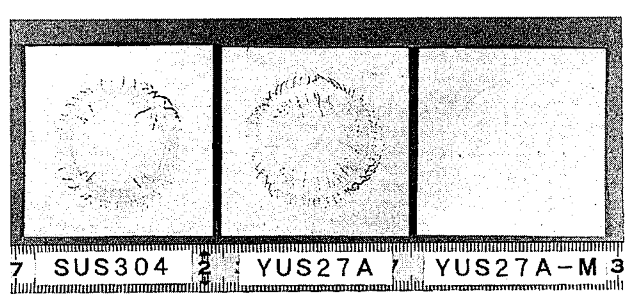

Photo 1 SCC susceptibility of YUS 27A-M

Table 7 Mechanical properties and formability of YUS 27A-M

Property	YUS 27A-M	YUS 27A	SUS 304
0.2% offset yield strength (N/mm²)	281	257	298
Tensile strength (N/mm²)	657	629	668
.Elongation (%)	60	56	52
Hardness Hv	163	146	159
Erichsen value (mm)	14.0	14.4	11.8
Limiting draw ratio (LDR)	2.13	2.13	2.00

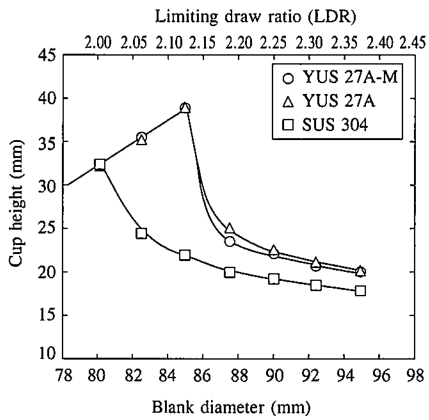

Fig. 14 Deep drawability of YUS 27A-M

4. Conclusions

Two austenitic stainless steels have been newly developed. One steel is designated YUS 110M and features formability comparable to that of SUS 304 for hot-water supply equipment and pitting corrosion resistance and crevice corrosion resistance equivalent to those of SUS 316. The other steel is designated YUS 27A-M and features SCC resistance superior to that of YUS 27A for appliances that require deep drawability and stretchability higher than those of SUS 304.

(1)The quality evaluation of conventional stainless steels with copper or silicon additions shows that the copper and silicon are also effective in neutral chloride environments. SCC resistance up to 130°C in a solution containing 200 ppm of Cl^- ions, which is the maximum permissible Cl^- ion concentration for tap water, can be accomplished by adding 2% each of silicon and copper to the base composition 18Cr-10Ni. The addition of 0.7%Mo imparted pitting corrosion resistance and crevice corrosion resistance comparable to those of SUS 316 and formability comparable to that of SUS 304.

(2)The addition of 1.5%Si without sacrificing formability is effective in imparting SCC resistance comparable to that of high-nickel SUS 304 to YUS 27A, which is used in applications requiring deep drawability and stretchability.

Making use of silicon and copper in this way, YUS 110M (18Cr-10Ni-2Si-2Cu-0.7Mo) and YUS 27A-M (17Cr-7Ni-1.5Si-2Cu) are suited for appliances for which conventional ferritic stainless steels lack sufficient formability and for applications in which formability is of particular importance.

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