Abridged version

KAWASAKI STEEL TECHNICAL REPORT
No.19 (November 1988)
Steel Pipe

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Ferritic stainless steels for automotive exhaust systems are reexamined for corrosion resistance and properties at elevated temperatures. Production process of the steels using conventional facilities for plain carbon steels in studied. Stainless steels have good corrosion resistance to inner condensate and outer road salt. Ti-stabilized type 409L is better than nonstabilized type 410L in both corrosive environments. Type 409L also has better properties at elevated temperature and better press formability, and is considered to be the optimum material for these automotive applications. It is shown that rolling by the high-productive tandem mill and optimizing the condition of the annealing process can provide stainless steel strips with sufficient quality of dimensions, surfaces, and properties.

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Characteristics of Stainless Steel for Automotive Exhaust Systems and Its Production by Tandem Cold Rolling*


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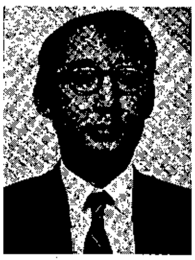
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Synopsis:

Ferritic stainless steels for automotive exhaust systems are reexamined for corrosion resistance and properties at elevated temperatures. Production process of the steels using conventional facilities for plain carbon steels is studied.

Stainless steels have good corrosion resistance to inner condensate and outer road salt. Ti-stabilized type 409L is better than nonstabilized type 410L in both corrosive environments. Type 409L also has better properties at elevated temperature and better press formability, and is considered to be the optimum material for these automotive applications.

It is shown that rolling by the high-productive tandem mill and optimizing the condition of the annealing process can provide stainless steel strips with sufficient quality of dimensions, surfaces, and properties.

1 Introduction

The fields of application of stainless steels are diverse and constantly expanding. In the production of stainless steels, particular importance has to date been attached to the brightness and beauty of the steel surface. In recent years, however, increasing attention has been given to areas of application in which the essential functions of high Cr steels, such as corrosion resistance and heat resistance, are important. A typical example is automotive exhaust systems, where cast iron and aluminized steels have conventionally been used. However, these materials are rapidly giving place to stainless steels for a variety of reasons: to achieve weight-savings aimed at fuel cost reductions, to respond to changes in the corrosive environment resulting from higher engine performance and improved exhaust cleaners, and to cope with externally-caused corrosion resulting from increased consumption of deicing salt in snow-prone areas.

Stainless steels for automotive exhaust systems must possess high-temperature characteristics and corrosion resistance, while being produciable at low cost. The selection of an optimum steel grade and examination of the manufacturing process were carried out from this standpoint.

Although AISI 409 is generally used in automotive exhaust systems, use of Kawasaki Steel's stainless steels R409L and R410L, which correspond to this steel grade, is discussed in this report. The report also describes an examination into a manufacturing process in which a high-productivity tandem mill for plain carbon steels is used in place of the conventional Sendzimir mill.

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2 Changes in Corrosive Environment of Automotive Exhaust Systems and Material Properties Required

Recent trends in the selection of material for automotive exhaust systems and required properties are shown in **Table 1**. Stainless steels are replacing conventional materials in exhaust manifolds, mufflers, and front and tail pipes.

The principal problems in connection with the exhaust manifold are weight reduction and higher operating temperatures. The conventional material for exhaust manifolds is cast iron. However, stainless steels are being adopted, permitting a reduction in the wall thickness of this part and a consequent reduction in weight aimed at lowering fuel consumption. This trend is especially marked in the U.S., mainly in compact cars where average fuel costs can easily be reduced, avoiding the so-called gas-guzzler tax. Reduction of wall thickness also makes it possible to raise the exhaust temperature of catalytic converters, which is considered effective in emission control.

Table 1 Properties required for materials of automotive exhaust system

Parts	Properties required	Material selection	
		Conventional	Substituting
Exhaust manifold	• Tensile, fatigue and creep strengths at elevated temperature	Cast iron	Stainless steel pipe (type 409, 439)
Front pipe	• Oxidation resistance • Formability • Corrosion resistance in condensate	Stainless steel pipe covered by aluminized steel pipe (type 409)	
Converter shell	• Fatigue strength at elevated temperature • Press formability	Stainless steel (type 409, 410)	
Middle pipe, muffler and tail pipe	• Corrosion resistances in condensate and road salt • Press formability	Aluminized steel	Stainless steel pipe (type 409, 410)

Material for exhaust manifolds must provide excellent high-temperature characteristics, since the operating temperature of this part may reach 800°C. In particular, durability under conditions of repeated heating and cooling is necessary.

Increasingly high requirements are being placed on materials for exhaust manifolds, in response to the elevated temperatures at which higher performance engines operate and the heat-insulation effect of noise-insulating materials.

Moreover, excellent formability is also required, because exhaust manifolds are worked and assembled by press forming and pipe bending.

In middle pipes, mufflers and tail pipes, conventional aluminized steel is being replaced by stainless steels to solve the problem of corrosion of the internal and external surfaces.

Internal corrosion is caused by the exhaust condensate. The pH-value of the condensate has changed due to the adoption of catalytic converter rhodium, and the distance between the catalytic converter and the muffler has changed with the adoption of the manifold converter, with the result that condensate generation conditions have changed[1], posing new problems. Moreover, the interval of compulsory automobile inspections has been extended from two to three years for new automobiles. This is significant because the service life of mufflers was formerly set to cover two inspections cycles, i.e. four years. To achieve the same two-cycle coverage, improved corrosion resistance was required.

Exterior corrosion is attributable to sea salt and road salt used in winter. The consumption of road salt has increased yearly, especially in North America, causing greater corrosion problems. Thus materials for mufflers must have corrosion resistance, as well as formability, particularly, suitability for hole-flanging.

3 Examination of Optimum Stainless Steel Grade

The company's stainless steels R409L and R410L, which have already been used in automotive exhaust systems, were examined with respect to the above-mentioned required properties. The chemical compositions of these steels are given in **Table 2**.

Table 2 Chemical composition of standards and typical examples

Steel grade		Ladle analysis value (wt %)							
		C	Si	Mn	P	S	Ni	Cr	Ti
R409L	Standard	≦0.030	≦1.00	≦1.00	≦0.040	≦0.030	≦0.60	10.50~11.50	6×C~0.75
	Typical example	0.010	0.50	0.50	0.025	0.005	0.10	11.20	0.15
R410L	Standard	≦0.030	≦1.00	≦1.00	≦0.040	≦0.030	≦0.60	11.00~13.50	—
	Typical example	0.012	0.35	0.35	0.025	0.006	0.07	12.13	—

3.1 Properties at High Temperatures

Parts such as the exhaust manifold, which are used in the vicinity of the engine where temperatures may be as high as 500°C, are required to provide the following properties. The two stainless steel grades were compared for these properties.

3.1.1 High-temperature oxidation resistance

Results of a cyclic oxidation test conducted at temperatures up to 900°C in ordinary air are shown in **Fig. 1**. At 800°C, R409L and R410L show almost equal oxidation resistance, and changes in weight are slight. A stable oxide film formed on the surface of R409L at 850°C, while accelerated oxidation began with R410L at this temperature. At 900°C, accelerated oxidation proceeded in both steels in about 100 h, forming a thick oxide films. This finding indicated that neither steel can be used at this temperature. Because the $\alpha \rightarrow \gamma$ transformation point of R410L is in this temperature range[2], it is susceptible to deformation due to the formation of the γ-phase at high temperatures or the $\gamma \rightarrow \alpha'$ transformation during cooling. Thus the applicability of R410L is limited by the transformation temperature rather than by the maximum temperature allowable in terms of oxidation resistance.

Although the test was conducted in ordinary air, oxidation is more intense in the type of atmosphere characteristic of automotive exhaust systems, i.e., in a high-humidity and low-oxygen atmosphere. Therefore, the maximum service temperature of these 11–12% Cr steels should be held to about 800°C.

3.1.2 High-temperature strength

Sheet specimens were subjected to a short-term tensile test at elevated temperature, with the results shown in **Fig. 2**. Both R409L and R410L stainless steels show a ferrite structure at the test temperatures. Although the strength of both steels decreases rapidly with increasing temperature, R409L showed slightly greater strength than R410L. Basically, the higher the content of alloy elements such as C, N, Cr, and Ti, the higher the strength at high temperatures. On the other hand, these elements cause the deterioration of oxidation resistance[3] and press formability. Thus the composition balance must be determined in accordance with required properties.

3.1.3 Creep characteristics

Results of rearrangement of the creep characteristic of sheet specimens at 500 and 700°C by the Larson-Miller parameter method are shown in **Fig. 3**. R409L is far superior to R410L in creep strength. In specimens including TIG weldments (produced using a Y308 1.2 mmϕ filler rod), rupture originated in the base metal. The creep strength of the weld zone and HAZ was higher than that of the base metal.

Furthermore, R409L was superior to R410L in the sag test at 800°C, as in the creep test (**Fig. 4**).

3.1.4 High-temperature fatigue strength

A repeated bending test was conducted on sheet specimens including weldments to investigate fatigue strength at high temperatures. A diagram of the test set-up is shown in **Fig. 5**, and a view of the test device is shown in **Photo 1**. By using a tapered specimen, it is possible to determine the area of lowest fatigue strength in the uniformly heated zone of a material including weldments. Heating was conducted with a two-turn type high-frequency induction heating device. Since material

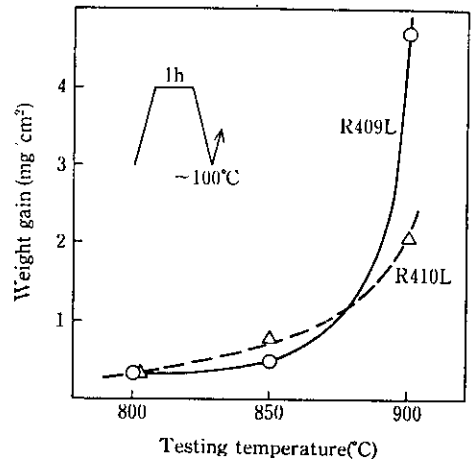

Fig. 1 Temperature dependence of steels in weight change after oxidation of 300 cycles in air at elevated temperature

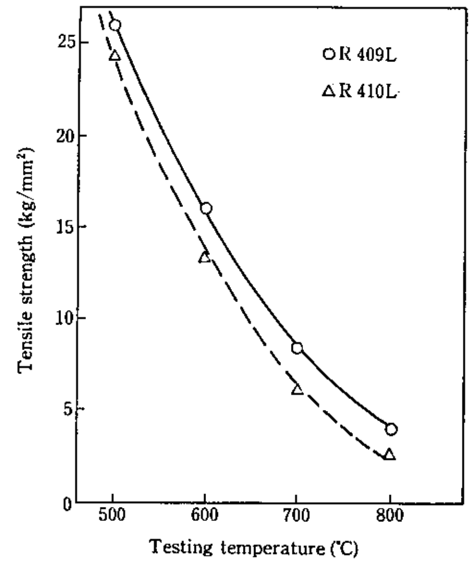

Fig. 2 Short time tensile strength of the stainless steels at elevated temperature

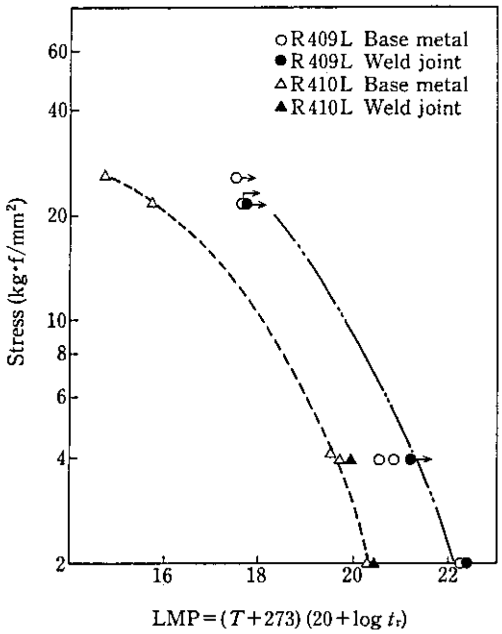

Fig. 3 Master rupture curves of the stainless steels for the results of creep test

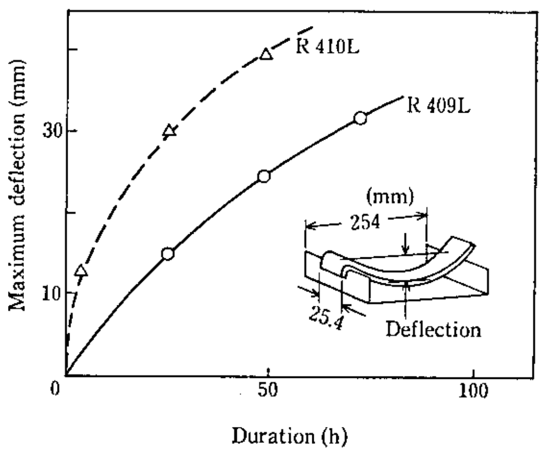

Fig. 4 Change in deflaction of the stainless steels by sag test at 800°C

strength varies according to the temperature distribution from the jig grip end to the vibration end, fatigue strength values relative to bending stress were not obtained. However, this method is convenient for making relative evaluations under the same conditions. The results are shown in **Fig. 6** as the relationship between strain amplitude and cycles to failure. In consideration of the capacity and response of the testing machine, 1.5 Hz was adopted for a 2.0-mm thick sheet at 500°C and 3.0 Hz for 2.5-mm thick sheet at 700°C. Although the two steels do not differ greatly in high-temperature fatigue strength, R409L is superior. In all cases, fracture occurred in the base metal, and neither the weld zone

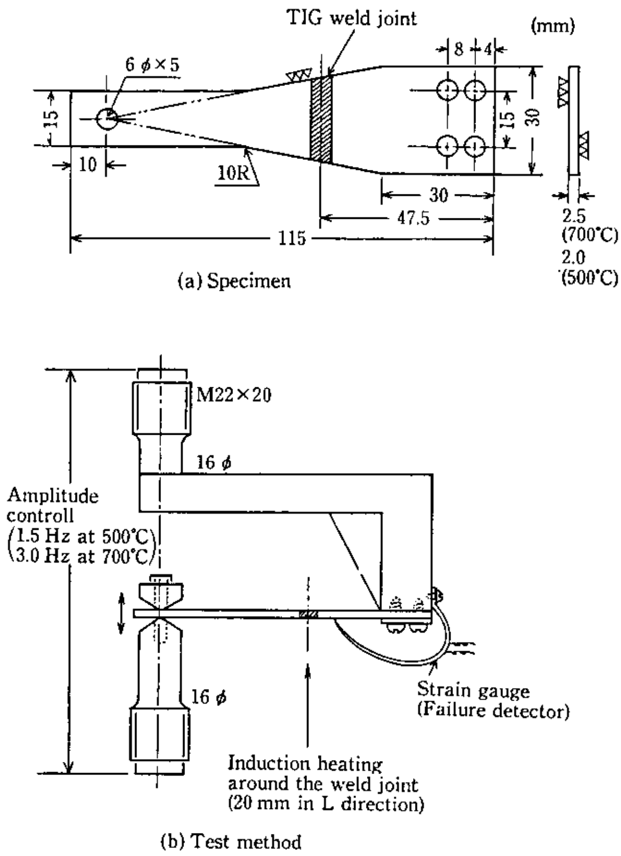

Fig. 5 Method of fatigue test at elevated temperature for tapered specimen with weld joint

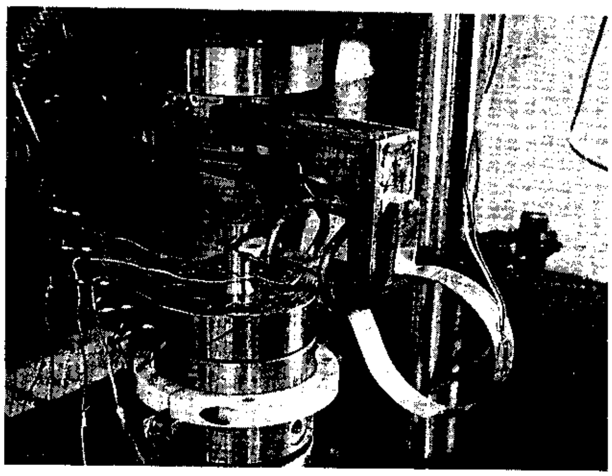

Photo 1 Fatigue test at elevated temperature

nor the HAZ showed weakness. As shown in **Photo 2**, failure occurred in the form of transgranular and intergranular cracks. In R409L, crack tips are more apt to branch out due to the formation of intergranular cracks.

As is apparent from the foregoing, R409L and R410L stainless steels have almost the same high-temperature

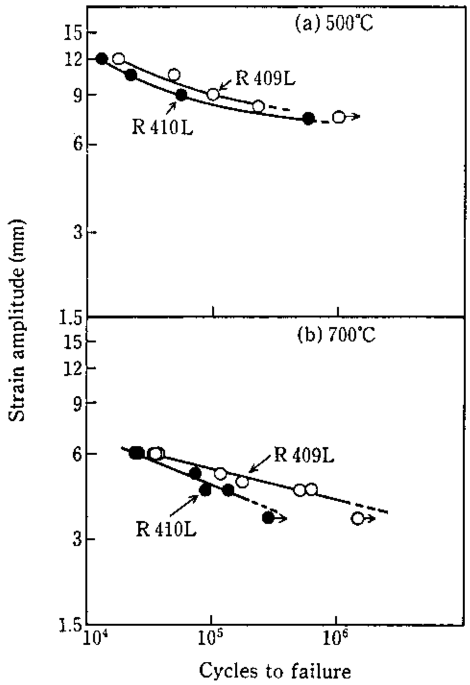

Fig. 6 Fatigue life of the stainless steels at 500 and 700°C

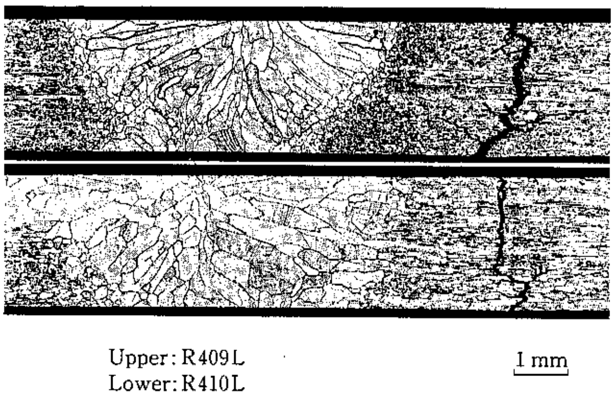

Photo 2 Optical micrographs of the specimen at the fatigue crack

properties. In all respects, however, R409L is slightly superior to R410L. Based on creep characteristics, it is apparent that R409L is the better suited for high-temperature area automotive exhaust system parts.

3.2 Corrosion Resistance

In examples from North America, almost all corrosion of automotive exhaust systems occurs in relatively low temperature areas, for example, in the middle pipe and following parts. Corrosion caused by condensate, i.e., in the pipe interior, accounts for 70% of corrosion, and that from salt damage, i.e., on the exterior surface, accounts for 30%[4]. It is thought that an increase in the

Table 3 Composition of synthesized condensate[1]

Reagent	Composition (wt %)
HCl	0.1
H_2SO_4	1.0
CH_3COOH	1.0
HCOOH	1.0

NH_4OH is added as to be pH 8

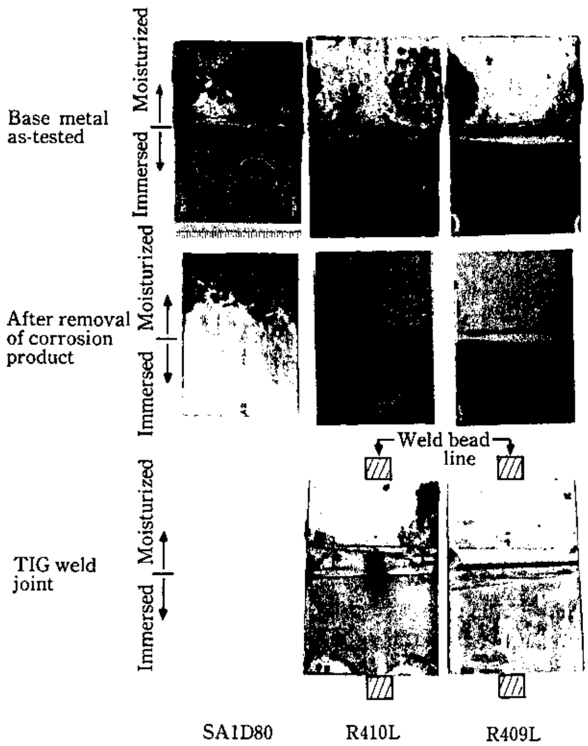

Photo 3 Corrosion test results in the synthesized condensate[2] (half immersion, 80°C, 4 weeks)

pH of condensate due to recent introduction of catalytic converter rhodium accelerates the corrosion of aluminized steel.

A half-immersion corrosion test was conducted in a synthesized condensate[1] formulated as shown in **Table 3**, to approximate the exhaust condensate at the muffler. This synthetic condensate contained Cl^- and SO_4^{--}, and had a pH adjusted to 8 using ammonia liquor. The specimen had as-sheared edges. Aluminized steel sheets JIS SA1D40 and SA1D80 of 1.5 mm thickness were used for purposes of comparison. The results are shown in **Photo 3**. Corrosion was severe at the vapor-liquid interface and in the vaporized area. Pitting corrosion was marked in the sheared edges in the stainless steels. However, general corrosion did not occur and the amount of corrosion was small. R409L stainless steel showed better corrosion resistance than

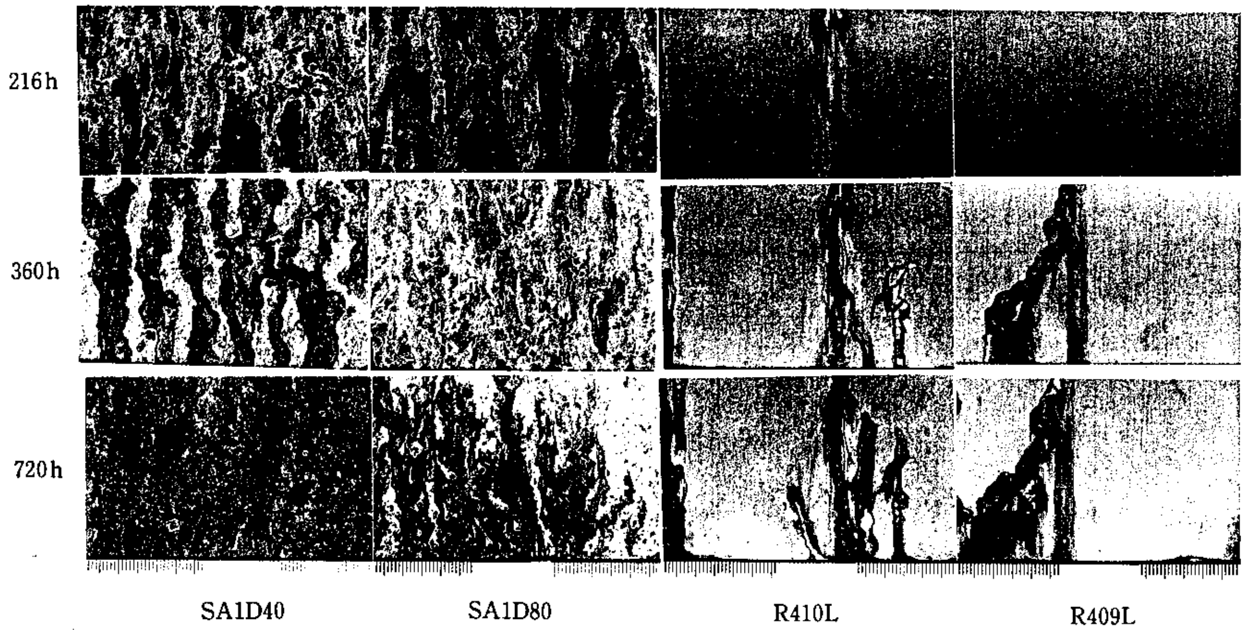

Photo 4 Results of salt spray test

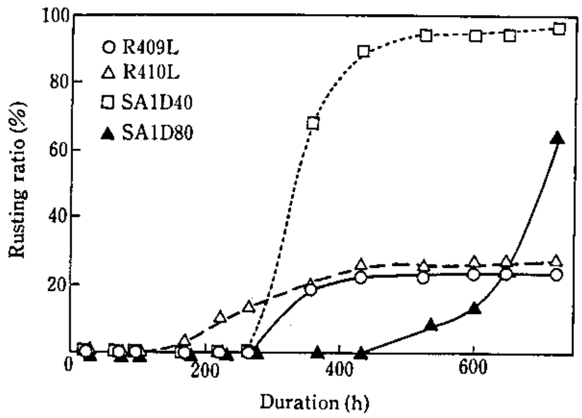

Fig. 7 Rusting ratio of the steels after long time exposure in the salt spray test (JIS Z2371, 5%NaCl, 35°C)

R410L. In the test on TIG weldments, slight pitting (0.2 mm in depth) with intergranular corrosion in the weld zone, corresponding to the air-liquid interface, occurred in R410L; hence the 409 type containing Ti as a stabilizing element was superior in corrosion resistance. General corrosion took place in a relatively short time in the aluminized steels used as comparison materials.

A long-term salt spray test was carried out to evaluate the exterior corrosion resistance. Results are shown in **Fig. 7** and **Photo 4**. Almost the same results were obtained with the stainless steels R409L and R410L, and rusting was slight even after 720 h. With the aluminized steels, rust formed over the entire surface after 720 h.

Thus both stainless steels, R409L and R410L, provide fairly good resistance to the types of corrosive environments affecting the internal and external surfaces of automotive exhaust systems, although the former is slightly superior.

3.3 Mechanical Properties and Formability

The mechanical properties and formability of R409L, R410L, and the aluminized steels are shown in **Table 4**. R409L, which contains Ti, has high r-values and is superior in press formability. Mufflers require hole-

Table 4 Mechanical properties of materials for the exhaust system (thickness = 1.5 mm)

Direction		YS (kgf/mm^2)	TS (kgf/mm^2)	El (%)	n*1)	r*2)	CCV (mm)	Er (mm)	Bore*3) expansion, λ
R409L	L	25.3	44.0	37.4	0.25	1.08			
	D	27.0	45.0	35.7	0.24	0.99	60.0	11.9	2.30
	T	27.6	45.1	34.4	0.23	1.40			
R410L	L	25.9	37.8	38.1	0.25	0.85			
	D	28.0	41.3	33.2	0.25	0.77	62.6	10.8	1.77
	T	28.0	40.9	34.3	0.25	1.18			
Aluminized steel (SA1D80)	L	25.2	33.9	43.8	0.18	0.99			
	D	26.2	34.9	40.7	0.18	0.80	60.1	12.4	2.07
	T	26.4	34.0	45.1	0.18	1.35			

*1) Calculated from 5-15% stress
*2) Calculated from 15% elongation
*3) $\lambda = D/D_0$ (D_0, original dia. of punched bore (15 mmϕ); D, expanded bore dia.)

flanging workability, a characteristic which can be evaluated[5] by $n(1 + r_{min})$. R409L is also suitable in this respect. The properties of the aluminized steels lay between those of R409L and R410L.

4 Examination of Optimum Manufacturing Process

After R409L was determined to be the more suitable material, an examination was made to determine the optimum manufacturing process. Results of this examination are described in this section. Stainless steels are ordinarily rolled on a Sendzimir mill, which imparts surface brightness. However, automotive exhaust systems do not require such good surface brightness. Cost reduction, which can be realized by high productivity, is a more important problem. Rolling on a tandem mill, normally used to produce plain carbon steels, is a possible means of achieving this aim.

An examination was made into problems with the manufacture of R409L stainless steel coils using equipment for plain carbon steels. A comparison between the conventional manufacturing process for stainless steels and the new process, which covers both stainless and plain carbon steels, is shown in **Fig. 8**. An APL (annealing and pickling line) was adopted for stainless steels as the annealing process after rolling, and a CAL (continuous annealing line) was adopted for plain carbon steels.

The production process for automotive exhaust systems includes the manufacture of high frequency welding pipe and press forming, both of which require good dimensional accuracy and formability. Therefore, a close examination was also made of these manufacturing steps.

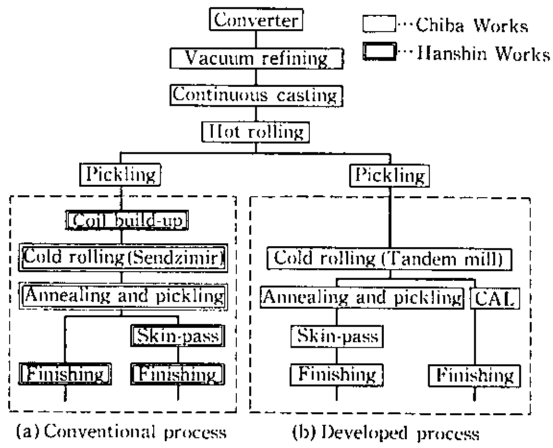

Fig. 8 Comparison of manufacturing process of conventional and developed ones

4.1 Cold Rolling

A five-stand mill was used to conduct tandem rolling. As shown in **Fig. 9**, this mill is equipped with AGC (automatic gauge control), and thickness accuracies of ±2% in the longitudinal direction are achieved with plain carbon steels. Since R409L stainless steel has an ultimate tensile strength of about 45 kgf/mm^2, equivalent to those of plain carbon steels, sufficient accuracy can be obtained. Examples of the thickness record for the tandem rolling of R409L are shown in **Fig. 10**. The stable portion has accuracies of 0.6 mm ± 6 μm, and sufficiently meets the ET tolerance (±5%) of JIS, even if the tolerance for the crown in the transverse direction is taken into consideration.

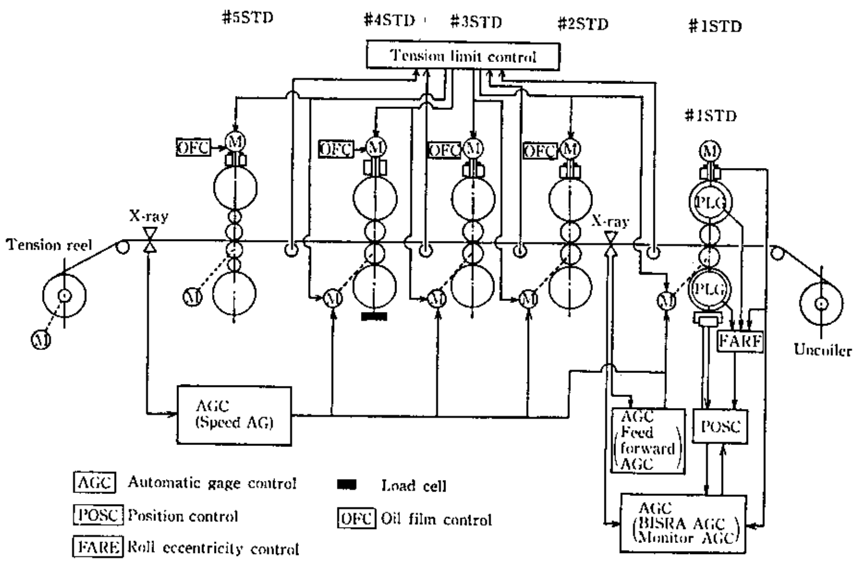

Fig. 9 Diagram of AGC system of 5-stand tandem cold mill

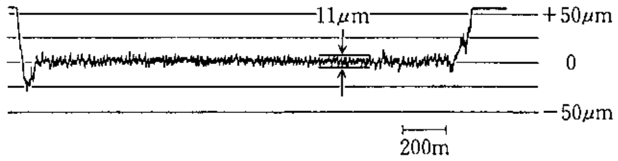

Fig. 10 Example of thickness record of tandem rolled R409L

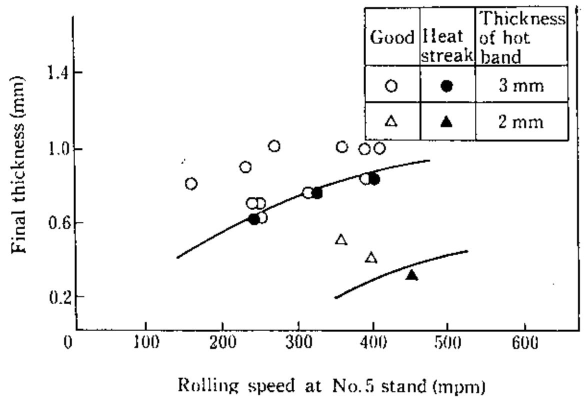

Fig. 11 Relation between rolling reduction and rolling speed on occurrence of heat streak

The relationship among final thickness, rolling speed, and the occurrence of heat streak for R409L is shown in **Fig. 11**. The heavier the rolling reduction and the higher the rolling speed, the more heat streaks tend to occur. Therefore, it is necessary to change the hot-rolled band thickness in accordance with final thickness.

The size availability shown in **Fig. 12** derives from the above-mentioned results. The size availability of products of small final thickness is determined in consideration of productivity, although it is also related to hot band dimensions.

The greatest problem with the tandem rolling of stainless steels is roll sticking defects, which occur during the roll-in and roll-out of the coil at the lead and tail ends. This problem does not occur with plain carbon steels; it is a phenomenon peculiar to stainless steels containing much chromium. To prevent this defect, reduction may be decreased as the ends of the strip pass the rolls. This measure, however, results in an increase in off-gauges, a problem that can be solved by using large-weight coils produced by welding in the hot band state. Welding is performed using laser to produce welds capable of withstanding the tension and deformation of rolling. The weld joint structure obtained with a 10-kW laser features a much narrower HAZ than that with TIG welding, and thus contributes to stable rolling. The fundamental solution to the problem of off-gauge ends,

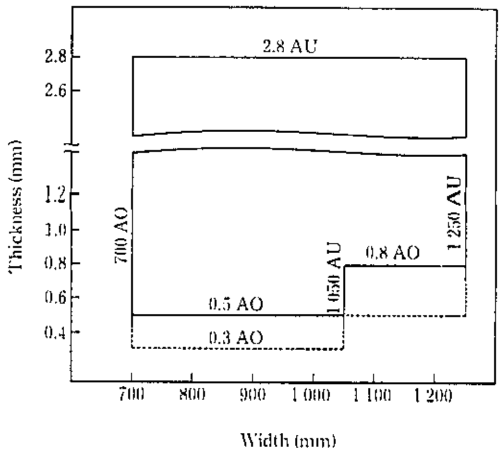

Fig. 12 Size availability of R409L and R410L by tandem rolling process (Mill edge coil; AO, and over; AU, and under; solid line, standard availability; broken line, special availability—to be negotiable)

however, is the use of a fully continuous mill; plans are underway for this modification.

4.2 Final Annealing

R409L is a Ti-bearing stainless steel and displays good formability if sufficiently annealed. In determining annealing conditions, an examination was made as to whether good mechanical properties can be obtained in high-temperature, high-speed operation if the composition balance is adjusted and the Ac_1 temperature ($\alpha \rightarrow \gamma$ transformation temperature) is increased. The relationship between annealing conditions and mechanical properties was investigated with this temperature increased to 1027°C and the Cr and Si contents adjusted. The results are shown in **Fig. 13**. Elongation decreases abruptly above the transformation temperature, and good elongation is not necessarily obtained even if the annealing temperature is increased by increasing the transformation temperature. Based on these results, therefore, the Ac_1 temperature in actual operation is estimated for each coil from the chemical composition balance in such a way that the annealing temperature does not exceeded the transformation temperature. Actual mechanical properties of R409L stainless steel sheets produced recently are shown in **Fig. 14**.

In a CAL used in the continuous annealing of plain carbon steels, the partial pressure of hydrogen is low and the dew point is high for stainless steels, and especially for those containing Ti, making it impossible to prevent oxidation during annealing. Oxide scale formed by this oxidation, although very thin, causes die sticking and a deterioration of corrosion resistance. For this reason, CAL-processed stainless steels can be used only for certain applications unless pickling or surface grinding is first conducted.

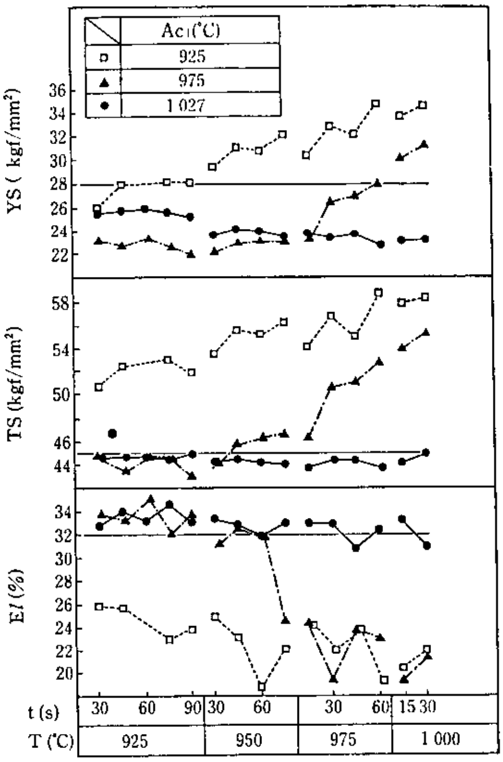

Fig. 13 Influence of annealing temperature (T) and holding time(t) on mechanical properties of R409L

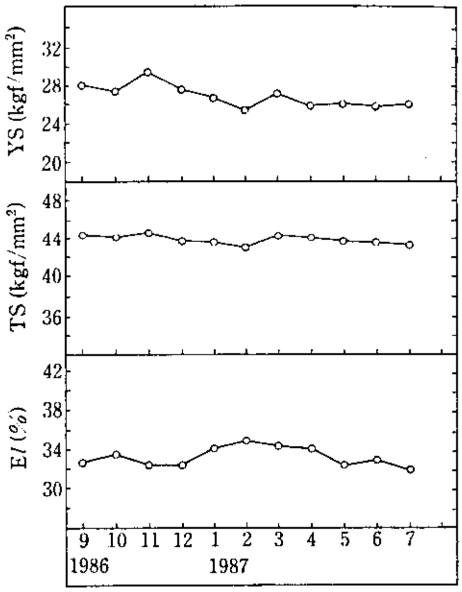

Fig. 14 Stable results in mechanical properties of R409L in recent years

For this reason, R409L stainless steels tandem rolled are finished on a production facility for stainless steels, in which electrolytic descaling in neutral salt and pickling are conducted.

5 Conclusions

An examination was made to determine the optimum grade of stainless steel for use in automotive exhaust systems and to establish a high-efficiency manufacturing process for this steel grade.

(1) Although R409L and R410L stainless steels have very similar properties at high temperatures, R409L is slightly superior in all respects.

(2) R409L is slightly superior to R410L in resistance to corrosion of the internal and external surfaces of automotive exhaust systems.

(3) Concerning mechanical properties and formability, R409L has higher *r*-values and superior hole-flanging workability to R410L and aluminized steels. Thus R409L is also best suited from this viewpoint.

(4) A tandem mill for plain carbon steels can be used to roll this material very efficiently, and high-quality products can be obtained if appropriate finish annealing conditions are adopted.

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