KAWASAKI STEEL TECHNICAL REPORT
No.46 (JUNE 2002)
"Environment-friendly Steel Products" and
"Environment Preservation Technology"

Ferritic Stainless Steels and Pipes for Automotive Exhaust Systems to Meet Weight Reduction and Stricter Emission Requirements

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High formability heat-resistance ferritic stainless steel and pipes for automotive exhaust system parts were developed to reduce auto weight and meet stricter emission requirements by making full use of the advanced production facilities recently constructed at Chiba Works. The average *r*-value of the newly developed stainless steel was improved by more than 1.3 times in comparison with the conventional steel while retaining the same level of heat resistance. This increase in the *r*-value lead to a remarkable improvement in various forming properties which are important for automotive exhaust system parts, including (1) limit drawing ratio, (2) stretch flanging ratio, (3) limit expansion ratio of pipe, and (4) thickness reduction ration of pipe after bending. In particular, the formability of the newly developed stainless steel pipes was nearly equal to that of conventional stainless steel pipes after stress relief annealing.

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1 Introduction

In recent years, with attention being drawn to global environmental problems, there has been strong demand for improvement in the automotive exhaust gas purification ratio in many countries. Various laws and regulations have been enacted or are proposed, including the LEV and LEV-II standards in the United States, the EU2000 and EU2005 standards in Europe, and a trend toward significantly stricter exhaust gas regulations is expected in the next several years. To meet these stricter regulations, improved exhaust gas purification immediately after the engine is started (cold start) is an extremely important task. This is because the temperature of the catalytic converter is low immediately after starting, making it difficult to proceed the purification reactions for NO_x, HC, and CO in the exhaust gas. Effective countermeasures for this problem are either (1) increasing the temperature of the exhaust gas, or (2) reducing the thickness of the exhaust manifold material in order to reduce its heat capacity.[1] As an additional advantage of (2), reducing the thickness of the material also contributes to weight reduction. Since high heat resistance is required in materials that are to be used with the latter method, stainless steel has increasingly been adopted as a substitute for cast products.[2] In many cases, the exhaust manifold is designed with a complex shape so as to fit into a limited space. Therefore, if the formability of the material is not adequate, it may not be possible to form the part to the specified shape, or the reduction in the thickness of the sheet after processing may be excessive. From three standpoints, the most commonly used material in recent years has been 15%Cr type ferritic stainless steel (Type 429Nb; Kawasaki Steel standard R429EX)[3], which has a relatively good balance of heat resistance and formability. However, with requirements for improved formability becoming even stricter, material maker have been required to develop a stainless steel that can satisfy both formability and heat resistance.

To respond to these requirements, Kawasaki Steel successfully realized an improvement of more than 30% in the *r*-value of the conventional heat resistant stainless

* Originally published in *Kawasaki Steel Giho*, **33**(2001)2, 72-76

steel for exhaust manifolds (Kawasaki Steel standard R429EX) by applying advanced process technology, while retaining a composition that provides excellent heat resistance.

This article describes the results of the deep drawability, stretch flangeability, pipe expansion, and bending properties, which are important properties for forming exhaust manifolds, by comparing the properties of the newly developed steel (high formability R429EX) with those of the conventional steel.

2 Directions for Improvement of Formability

In processing exhaust manifolds and other high temperature exhaust system parts, high *r*-values tend to be required due to an orientation toward forming complex one-piece parts. It has long been known that there are four main methods of obtaining high *r*-values in mild steel, these being (1) increasing the reduction ratio in cold rolling, (2) coarsening the microstructure of the final annealed steel sheet, (3) reducing the content of solid solution C, and (4) refining the microstructure of the hot rolled steel sheet.[4]

On the other hand, it is also well known that the average *r*-value of ferritic stainless steel increase remarkably when reduction during cold rolling exceeds approximately 70%.[5] In the range of thin sheet thickness of 1 mm or under, the *r*-value can easily be improved by increasing the cold rolling reduction ratio. However, the necessary cold rolling reduction ratio cannot be adequately secured in the thickness range of 1.5~2.5 mm, which is the major for exhaust manifold materials, and it had therefore been considered difficult to improve the *r*-value by this method. The above-mentioned method (2) coarsening the microstructure of final annealed sheet is also conceivable as a method of realizing high *r*-values, but because increasing the grain size tends to cause surface roughness after forming, there are limits to this method for use with exhaust manifold materials. For the reasons mentioned above, research was carried out aimed at realizing high *r*-values in ferritic stainless steels by either reducing the content of solid solution C or refining the microstructure of the hot rolled material. The test material for this work was Type 429Nb (Kawasaki Steel standard R429EX), which is a conventional major steel for exhaust manifolds. The composition of this material is listed in **Table 1**.

Table 1 Chemical compositions of steel used

(mass%)

C	Si	Mn	Cr	Ni	N	Nb
0.008	0.86	0.37	14.6	0.35	0.006	0.44

3 Test Materials and Experimental Procedure

3.1 Test Materials

Hot rolled steel sheets (developed steel) were produced by a hot rolling control process for realizing high *r*-values that maximizes the effects of the methods (3) reduction of solid solution C and (4) refinement of the hot rolled microstructure, which were described in the previous chapter. The microstructure of the developed steel showed finer recrystallization than the products of the conventional process. The results of an analysis of the content of precipitated Nb (insoluble Nb) and the aging index (A.I.), which is an index of the content of solid solution C, are shown in **Fig. 1** for these two materials. In the analysis of insoluble Nb, the content was determined by quantitative chemical analysis after constant-potential electrolytic extraction using an acetylacetone type electrolyte. The aging index was evaluated from the amount of deformation stress increase due to the aging treatment at 300°C for 30 min, in 7.5% tensile prestrain specimen using JIS 5 test pieces taken in the rolling direction. From Fig. 1, the product of the hot rolling control process for realizing high *r*-values (developed steel) contained a larger amount of precipitated Nb and also had a lower A.I. value. It is therefore considered that a larger amount of C in the hot rolled steel sheet was fixed by Nb, and as a result, the content of solid solution C was reduced.

Cold rolled and annealed steel sheets with thicknesses of 2 and 1.5 mm were manufactured using two types of hot rolled steel sheets, which were produced by the hot rolling control process for realizing high *r*-values and the conventional hot rolling process and then applying the same conditions in the processes after hot rolling. The properties of these materials were measured, and the various properties obtained were compared.

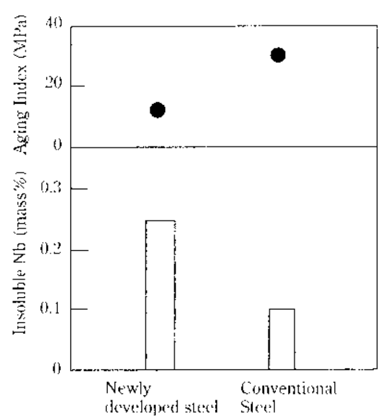

Fig. 1 Comparison of insoluble Nb content and aging index (A.I.) of hot bands between newly developed and conventional stainless steels

3.2 Experimental Procedure

3.2.1 Formability of cold rolled and annealed steel sheets

The properties of YS, TS, El, n-value, and r-value at room temperature were measured in accordance with JIS G0567 using JIS 13 B test pieces. The strain conditions for the n-value and the r-value tests were 5–15% and 15% strain, respectively. The average values of these properties were obtained using the following equation.

$$\text{Average } X = (X_L + 2X_D + X_C)/4$$

Here, X_L, X_D, and X_C are the properties of X in the 0°, 45°, and 90° directions, respectively, relative to the rolling direction.

The deep drawing property was evaluated in terms of the limit drawing ratio (diameter of test piece/33) using a punch with a diameter of 33 mm and test pieces with a thickness of 2 mm and diameters ranging from 66~76 mm. The dice shoulder radius was 3.5 mm, and the wrinkle suppressing force was set at 9.8 kN. Vinyl sheet was applied to the steel sheet on the dice side. To evaluate stretch flangeability (hole expanding property), a hole with a diameter of 10 mm was punched in the center of a 2 mm thick test piece, and hole expanding was performed from the side opposite to that where burr occurred by using a conical punch with a tip angle of 60°. The hole diameter at which cracking was initiated at the edge of the hole was measured, and the average value of three measurements, $n = 3$, was taken as a representative value, using the ratio (%) of (hole diameter at time of cracking—initial hole diameter) to the initial hole diameter as the stretch flanging ratio (λ). The burr was removed by grinding.

3.2.2 Formability of ERW pipe

Using the two types of material described in section 3.1 with thicknesses of 1.5 mm, electric resistance welded (ERW) pipes with a diameter of 42.7 mm were manufactured. In the case of the ERW pipes that were produced from the cold rolled and annealed steel sheets (1.5 mm thickness) produced by the conventional process, pipes were also prepared for testing for comparison purposes by performing strain relief annealing at approximately 900°C.

Limit expansion (pipe expansion property) was evaluated using the limit expansion ratio. In performing pipe expansion, the edge of the ERW pipe was first conditioned by grinding, and a six sheet type segment was then inserted into the pipe. The expansion ratio was increased successively under the conditions of 1.25D, 1.35D, 1.45D, and 1.5D at a rate of approximately Δ 0.1D/s. Tests were performed repeatedly with 10 pieces, and the expansion ratio at which even one piece cracked was taken as a limit expansion ratio.

To evaluate the bending property of the ERW pipes, 90° bending was performed at a bending radius of 50 mm. The thickness of the material was then measured by an ultrasonic method, and the bending property was evaluated in terms of the ratio of thickness reduction.

4 Experimental Results and Discussion

4.1 Mechanical Properties of Cold Rolled and Annealed Steel Sheets

Table 2 shows the mechanical properties of cold rolled and annealed steel sheets with thickness of 1.5 and 2 mm which were produced from hot rolled sheets.

The properties of YS, TS, El, and r-values of the cold rolled and annealed steel sheets which were produced by the process route that included the hot rolling control process for realizing high r-values (hereinafter referred to as the developed steel) were similar to those of sheets produced by the conventional process (hereinafter referred to as conventional steel). On the other hand, the average r-value of the developed steel was more than 30% higher than that of the conventional steel. A comparison of formability between the cold rolled and annealed steel sheets, and the related discussion are described in the following.

4.2 Deep Drawing Property

Figure 2 shows the results of a deep drawing test. **Photo 1** shows examples of the appearance of the developed steel and conventional steel after forming. In comparison with the limit drawing ratio of 2.0 for the conventional steel, that of the developed steel was substantially increased, to approximately 2.3. The cylindrical forming performed in this experiment was typical deep drawing forming, which is accompanied by compressive flange deformation. As the mechanism of rupture, rupture is caused by the stress excess at the ruptured part due to the squeezing force acting at the flange part. The deep drawing property depends on the mutual relationship between the deep drawing forming force and the rupture load of the material (load at which

Table 2 Mechanical properties of R429EX stainless steels produced by newly developed and conventional processes

Thickness: 2 mm

	YS (MPa)	TS (MPa)	El (%)	r-value
Developed steel	330	488	34	1.5
Conventional steel	343	479	34	1.1

Thickness: 1.5 mm

	YS (MPa)	TS (MPa)	El (%)	r-value
Developed steel	325	496	33	1.6
Conventional steel	340	490	33	1.2

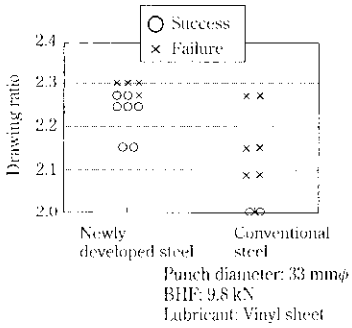

Fig. 2 Comparison of deep drawing property between newly developed and conventional steels

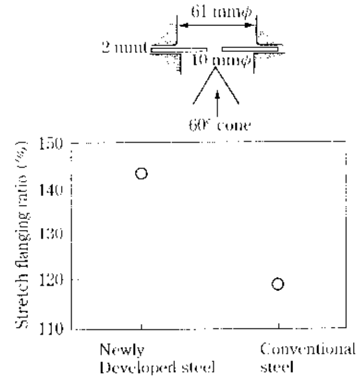

Fig. 3 Comparison of stretch flanging ratio between newly developed and conventional stainless steels

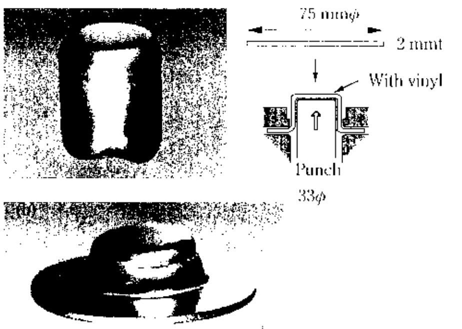

Photo 1 Comparison of appearance after deep drawing test between (a) newly developed stainless steel (deep drawing ratio = 2.27) and (b) conventional stainless steel (deep drawing ratio = 2.27)

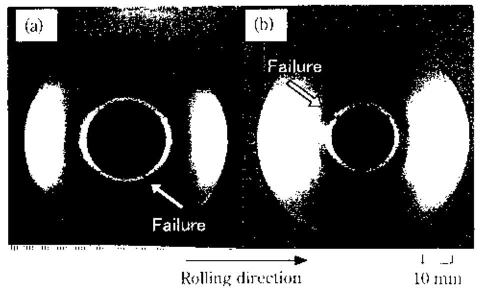

Photo 2 Appearance of test pieces after stretch flanging test, (a) newly developed stainless steel, (b) conventional stainless steel

rupture occurs during drawing). It is well known that higher r-values are advantageous for drawing forming because, in compressive flange deformation, as the r-value increases, the material reduced more easily in the circumferential direction, and the inflow of material at the flange part is easy. Consequently, the deep drawing force is reduced.[6] Because there were virtually no differences in the mechanical properties between the developed steel and the conventional steel except their r-values, the excellent limit drawing ratio of the developed steel is considered to be an effect of the r-value increase.

4.3 Stretch Flanging

Figure 3 shows the results of a stretch flanging test, and **Photo 2** shows an example of appearance of specimen after forming. The value of λ for the developed steel was 144%, which was remarkably improved from 119% of the conventional steel. As indicated by the arrows in Photo 2, the positions where cracking occurred in all the samples were the r_{min} direction (D direction).

Although many factors affect the stretch flanging

Table 3 Comparison between results of stretch franging test and the parameter of Ito's theory[7]

	Experimental results			Parameter of Ito's theory
	λ (%)	r_{min}	n-value	$n(1 + r_{min})$
Developed steel	144	1.12	0.19	0.40
Conventional steel	119	0.77	0.18	0.32

ratio, the developed steel and conventional steel showed similar values in all cases for YS, TS, El, n-value, and the anisotropy of these properties, and the final grain size, cleanliness, and the Charpy transition temperature. Therefore, the main difference was only the r-value. Ito et al.[7] studied the effects of the n-value and r-value on λ by using the finite element method, and concluded that λ is dependent on $n(1 + r_{min})$. Here, the terms, n and nr_{min} are uniform elongation and the minimum value of local elongation, respectively. The results of a comparison of the $n(1 + r_{min})$ of the developed steel and the conventional steel are listed in **Table 3**. Because there was virtually no difference in the n-value, r_{min} influences this parameter. In view of the fact that cracks started in the r_{min} direction in all cases of the specimens that were

Table 4 Mechanical properties of ERW pipes according to JIS 11

	Plate	Pipe			
	1.5 mmt	1.5 mmt × 42.7 mmϕ			
	$\bar{r}$-value (JIS 13 B)		YS (MPa)	TS (MPa)	El (%)
Newly developed steel	1.6	As rolled	465	511	49
Conventional steel	1.2	As rolled	438	488	50
	1.2	After stress relief annealing	299	501	51

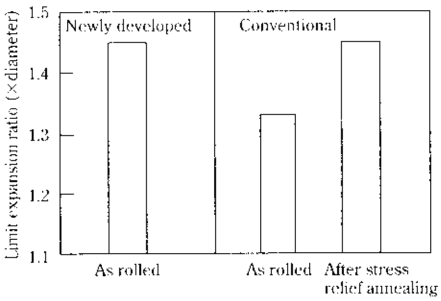

Fig. 4 Comparison of limit expansion ratio between newly developed and conventional stainless steel ERW pipes

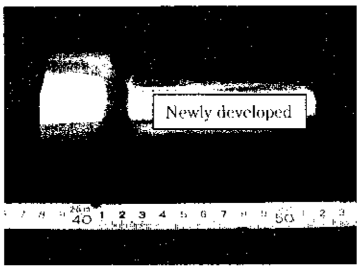

Photo 3 Appearance of ERW pipe (1.5 mm$t$ × 42.7 mmϕ) after expansion test (Expansion ratio = 1.45D, D: Diameter)

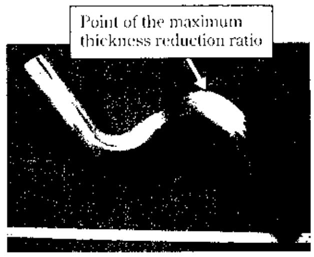

Photo 4 Appearance of ERW pipe of newly developed stainless steel after 50 mmR-90° bending (3 points)

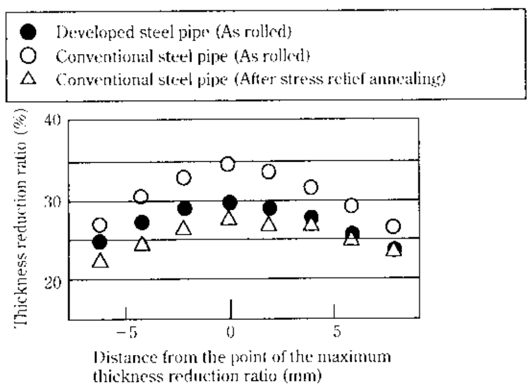

Fig. 5 Comparison of thickness reduction ratio after 90° bending between newly developed and conventional stainless steel pipes

tested in this work (Photo 2) and in consideration of the results shown in Table 3, it is considered that the improvement in the stretch flangeability of the developed steel was attributable to the improvement in r_{min}, which reflected an improvement in local elongation.

4.4 Mechanical Properties of ERW Pipe

Table 4 shows the mechanical properties of ERW pipe with a diameter of 42.7 mm and a thickness of 1.5 mm, and the r-values of the cold rolled and annealed steel sheets. In these three types of ERW pipes, YS of the developed steel was slightly high, but no large differences were observed in TS or El.

4.5 Expansion Ratio of ERW Pipe

Figure 4 shows the results of a pipe expansion test. The limit expansion ratio of the conventional steel was 1.35D, and that of the annealed pipe was 1.45D. On the other hand, the limit expansion ratio of the developed steel was 1.45D even when annealing was not performed, and thus has improved to a level equivalent to that of the conventional steel after annealing. **Photo 3** shows the appearance of a pipe of the developed steel after 1.45D expansion. Because the r-value of the developed steel was higher than that of the conventional steel, the features of the developed steel included (1) resistance to thickness reduction and (2) improvement in local elongation. It is considered that the limit expansion ratio increased as a result of these improvements.

4.6 Thickness Reduction Ratio of ERW Pipe After Bending

Photo 4 shows an example of bending forming. The part indicated by the arrow in the photo is the point with the maximum thickness reduction ratio. **Figure 5** shows the thickness reduction ratio in the longitudinal direction

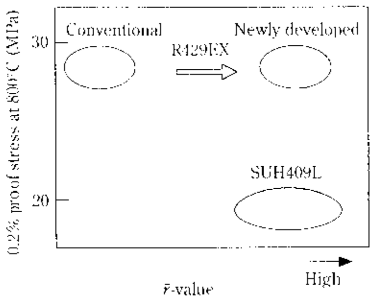

Fig. 6 Relationship between 0.2% proof stress at 800°C and $\bar{r}$-value (2 mm$t$) at room temperature

of the ERW pipe taking the point of maximum thickness reduction ratio as an origin. The thickness reduction ratio of the developed steel was smaller than that of the conventional steel, and has improved to a level near the value of the conventional steel after annealing.

4.7 Heat Resistance and Formability of Developed Steel Relative to Other Materials

It was clarified that the microstructure, chemical composition, and content of insoluble Nb and other precipitates of cold rolled and annealed steel sheets of the developed steel are virtually the same as those of the conventional steel, and heat resistance properties such as high temperature strength, high temperature fatigue resistance, oxidation resistance, high temperature salt damage resistance, and others were also on the same level. The properties and the test conditions were described in the previous articles.[8]

Figure 6 shows the relationship of the high temperature proof stress at 800°C and the average r-value (2 mm in thickness) at room temperature of the developed steel, conventional steel, and SUH409L. With the developed steel, high temperature proof stress on the same level as that of the conventional steel was secured, and the average r-value at room temperature was improved to a level equivalent to or better than that of SUH409L, which has the highest formability of the existing ferritic stainless steels.

5 Conclusion

Accompanying stricter regulations applied to automotive exhaust gas in recent years, the service environment for stainless steels has becoming increasingly severe. Therefore, for applications in high temperature environments, as represented particularly by the exhaust manifold, front pipe, and outer shell material for the catalytic converter, there has been increasing demand for the development of stainless steels that provide both excellent heat resistance and excellent formability. In order to meet these requirements, Kawasaki Steel carried out research and development aimed at improving the formability of its high heat resistance stainless steel R429EX, and has successfully attained remarkable improvements in the deep drawing property, stretch flangeability, pipe expansion ratio, and pipe bending formability of this material. In the activities, the advanced hot rolling facilities at Chiba Works and other technologies were practically utilized. Use of the newly developed steel is considered to offer a large number of advantages, including increased freedom in design, weight reduction by thickness reduction of the material, process omission of the strain relieving annealing for pipes, and other benefits.

In the future, a trend toward stricter regulation of exhaust gas is foreseen in all countries. Because Kawasaki Steel's stainless steel R429EX with high heat resistance and high formability can meet these stricter regulations, increasing adoption of this steel, which will contribute to a cleaner environment, is expected.

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