

Development of Material for Lightweight Catalytic Converter

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ABSTRACT

High-strength ferritic stainless steel HSS430CU has been developed as a material for use in catalytic converters. This material has superior strength at elevated temperatures and excellent press-forming properties.

HSS430CU does not contain the expensive element Mo that is normally added to the conventional high-strength ferritic stainless steel that is represented in Type444. Instead, Cu is added, which achieves equal or better high-strength properties. This material combines both the workability and strength properties required for catalytic converters. These properties are achieved as follows: superior workability is ensured by incorporating Cu, which is required for high strength, into solid solution when the materials are still raw materials, prior to press-forming; and high strength is ensured once the part is mounted in the vehicle, when heat energy is received as a result of exhaust gas, causing the Cu that was incorporated into solid solution to precipitate as fine ϵ -Cu crystals.

When this material was used in the catalytic converter for the 2014 model year FIT, the high-strength-providing properties of the material were utilized to reduce the plate thickness by 20% or greater. In addition, that superior workability enabled parts that had previously been formed as two pieces to be integrated into one piece, and it reduced weight while simultaneously cutting costs as well.

1. Introduction

Environmental awareness has increased in recent years, and as a result, various industries are pursuing efforts to cut CO₂ emissions. The automobile industry is also investigating the improvement of fuel efficiency through efforts such as increasing power-train efficiency, electrification, and weight reduction. Measures are also being implemented for the exhaust system, which has a great need for weight reduction. These include exchanging iron products with press components that use stainless steel. Presently, the main type of stainless steel plate that is used in catalytic converters is ferritic stainless steel, such as Type409L (11Cr-0.2Ti) and Type429M (14Cr-1Si-0.4Nb). When weight is further reduced by making the plates thinner, endurance reliability must be enhanced, requiring the use of high-strength ferritic stainless steel, represented by Type444 (18Cr-2Mo-0.4Nb). However, Type444 contains Mo, an expensive, rare metal element, inevitably increasing the part cost.

This paper introduces the ferritic stainless steel HSS430CU that was developed, which combines both high strength and high workability and does not contain Mo. It

also introduces the catalytic converter for the 2014 model year FIT that achieved reduction of weight and cost by using HSS430CU.

2. Development Goals

2.1. Catalytic Converter Weight Reduction

The overall structure of the catalytic converter for the 2008 model year FIT is shown in Fig. 1, and the weight percentages of its materials are shown in Fig. 2. Except for some of its components (the catalyst, the catalyst carrier holding mat, the flange, and the nuts), a catalytic converter uses stainless steel, which makes up approximately 70% of the total weight. Therefore, in order to decrease the weight of the catalytic converter, it is important for the weight of the stainless steel parts to be reduced. In order to decrease the weight of the stainless steel parts, it is necessary to make the plates thinner by increasing the strength of the stainless steel itself, and to decrease joint structures by performing integral press-forming of the parts that had been welded as lap joint structures. To accomplish this, the strength of the stainless steel needs to be increased, and workability also needs to be improved to perform integral press-forming of

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components that are difficult to form. In this development, integral press-forming was investigated with focus on Part A shown in Fig. 1.

2.2. High-Strength Stainless Steel Development

There are two types of stainless steel used in exhaust system parts: ferritic and austenitic. The coefficient of thermal expansion of austenitic stainless steel is approximately 1.5 times that of ferritic stainless steel. Therefore, when the austenitic type is used as the material for a catalytic converter, which undergoes cooling and heating cycles from high to low temperatures during vehicle operation, it is repeatedly exposed to high thermal stress, making durability an issue. Also, austenitic stainless steel contains Ni, which makes it expensive. As a result, a high-strength ferritic stainless steel similar to Type429M, which is the ferritic stainless steel currently used in mass-produced vehicles, has been developed.

First, four targets below in relation to the properties required for the material that is used in a catalytic converter were established. Because the stress that is generated increases as a result of decreasing the thickness of the

plates, strength at elevated temperatures was sought that was equivalent to or better than that of the pre-existing high-strength ferritic stainless steel Type444. We aimed for a material with oxidation resistance and corrosion resistance that were equal to or better than those of the conventional Type429M, since the environment in which the material was to be used was unchanged in terms of the demand for these resistance properties. Also, to reduce the weight and cost of the material, we aimed for press-forming properties that enabled the number of parts in the converter to be reduced as workability targets.

- (1) Strength at elevated temperatures: equivalent to or better than Type444
- (2) Oxidation resistance: equivalent to or better than Type429M
- (3) Corrosion resistance: equivalent to or better than Type429M
- (4) Workability: press-forming properties that enabled the number of parts used in the converter to be reduced.

3. Alloy Design Concept

As stated in chapter 1, the high-strength ferritic stainless steel, represented by Type444, contains the expensive chemical element Mo. When Mo is incorporated into solid solution as a metal, it serves as a chemical element that reinforces the solid solution and helps ensure strength at elevated temperatures. In addition, Mo is known to be effective at increasing oxidation resistance and corrosion resistance^{(1), (2)}. However, in order to reduce costs, Mo was not added to the material. Instead of using Mo as the means of increasing strength at elevated temperatures, focus was placed on Cu for the following reasons:

- (1) The cost of Cu is relatively stable;
- (2) Workability is good when the stainless steel material contains Cu in the form of a solid solution.; and
- (3) After the catalytic converter containing the material is installed in the vehicle, the Cu that had been incorporated into solid solution precipitates out as fine ϵ -Cu crystals as a result of heat energy from exhaust gas.

In order to achieve increased workability, which was the target of this development, the two property values, the elongation value and r -value, must be increased.

Figure 3 shows the relationship between the elongation and tensile strength of ferritic stainless steel (plate thickness 1.5 mm). Materials with high tensile strength have low elongation. Conversely, materials with high elongation have low tensile strength. Therefore, it is known to be difficult to simultaneously achieve both strength and elongation.

Meanwhile, ferritic stainless steel containing Cu has relatively good elongation when the Cu is incorporated into solid solution, but once the high-temperature region (from approximately 500°C to 700°C) is reached, a fine precipitant (ϵ -Cu) is formed, decreasing elongation and increasing strength⁽³⁾. Therefore, when press forming, which requires high elongation, good elongation is ensured by Cu being

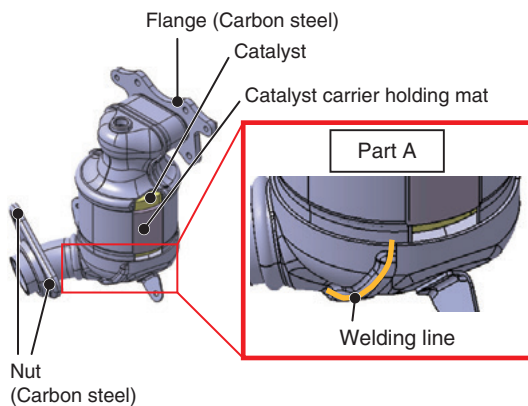


Fig. 1 2008 model year FIT catalytic converter

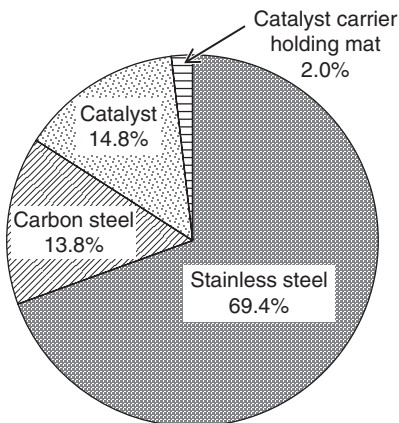


Fig. 2 Weight percentages of materials of 2008 model year FIT catalytic converter

incorporated into solid solution; and after the converter is installed in the vehicle, which is when high strength is required, strength can be increased by the ϵ -Cu precipitation effect caused by the heat energy from the exhaust gas.

Similar to elongation, the r -value is an index for evaluating workability. When tensile deformation of a material occurs, the r -value expresses whether it tends to contract in the thickness direction or the width direction. The r -value is expressed by Eq. (1).

$$r = \ln(W_1/W_0)/\ln(t_1/t_0) \quad (1)$$

r : r -value

W_0 , W_1 : The width of a test strip before and after tensile deformation

t_0 , t_1 : The thickness of a test strip before and after tensile deformation

Figure 4 shows the effect of the r -value on deep-drawability. The larger the r -value of a material, the more a deeply drawn shape can be made^{(4),(5)}. Therefore, the r -value is particularly important for a catalytic converter having a drawn shape. Figure 5 shows the effect of plate thickness on the r -value of Type429M. As the figure shows, since the r -value increases as the plate thickness decreases, it was expected that decreasing the plate thickness by using high-strength materials would increase r -value as a result. In

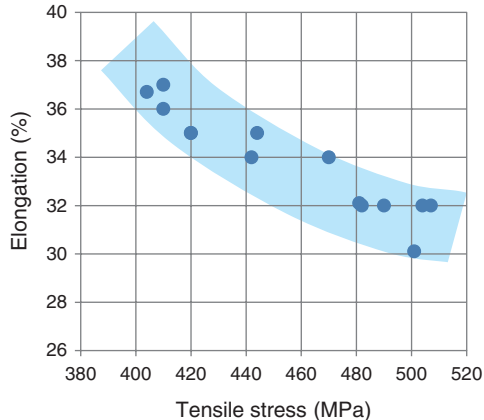


Fig. 3 Relationship between elongation and tensile stress

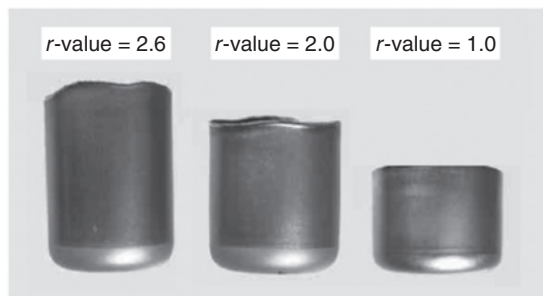


Fig. 4 Effect of r -value on deep-drawability

Table 1 Chemical composition (mass%)

	C	Si	Mn	Cr	Mo	Cu	Nb	N
Developed steel	0.007	0.8	0.2	17	-	1.3	0.5	0.007
Type429M	0.008	1.0	0.3	14	-	-	0.4	0.009
Type444	0.009	0.3	0.2	18	2	-	0.4	0.010

addition, we aimed to improve the r -value further by using a means to decrease C and N⁽⁶⁾, which prevent the r -value from increasing.

The addition of Cu is known to interfere with oxidation resistance. To improve oxidation resistance, it is essential to reinforce the oxide layer that exists on the surface of the stainless steel. Therefore, in this development effort, we aimed to help ensure oxidation resistance by increasing the quantity of Cr, which is effective at providing oxidation resistance.

It is known that the Pitting resistance equivalent (PRE) expressed by Eq. (2) can be used to estimate corrosion resistance⁽⁷⁾, and by increasing the quantity of Cr, which is the measure taken to increase oxidation resistance, it is also possible to help ensure corrosion resistance.

$$PRE = Cr + 3.3Mo \text{ (wt\%)} \quad (2)$$

The representative values of chemical composition established in the abovementioned investigation are shown in Table 1. The characteristics of the developed material composition are as follows.

- (1) In order to provide improved strength over the pre-existing material Type429M, Cu was added, and in order to ensure oxidation resistance and corrosion resistance, the quantity of Cr was increased.
- (2) The expensive chemical element Mo that is normally added to high-strength ferritic stainless steel was not added.
- (3) In order to improve workability, C and N were decreased to the extent possible.

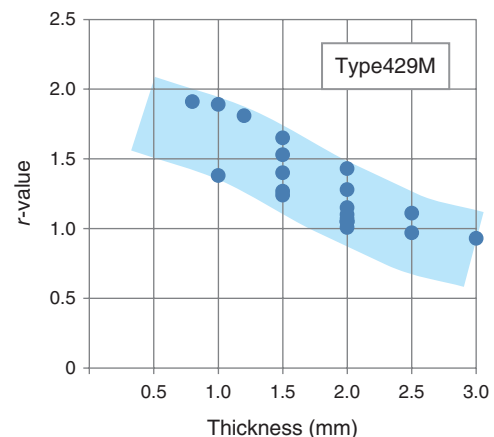


Fig. 5 Effect of plate thickness on r -value

4. Material Characteristics

4.1. Strength at Elevated Temperatures

Strength at elevated temperatures is a characteristic that is important when decreasing the thickness of stainless steel plates. In addition to the engine and other components conveying vibration to the exhaust system parts, in the high-temperature environment, thermal stress is produced as a result of engine heating and cooling cycles. Therefore, the material to be used at high temperatures must have both the properties of high-cycle fatigue strength and thermal fatigue strength.

Figure 6 shows the changes in hardness when thermal processing was performed at 600°C. Type429M, which does not contain Cu, does not have any changes in hardness and exhibits a constant value. In contrast, in the developed material, ϵ -Cu precipitates during thermal processing, and an increase in hardness is observed as a result.

Figure 7 shows the results of the high-temperature tensile test. Due to ϵ -Cu precipitation, the developed material has higher tensile strength than Type429M in all temperature regions, and it retains equal or better strength

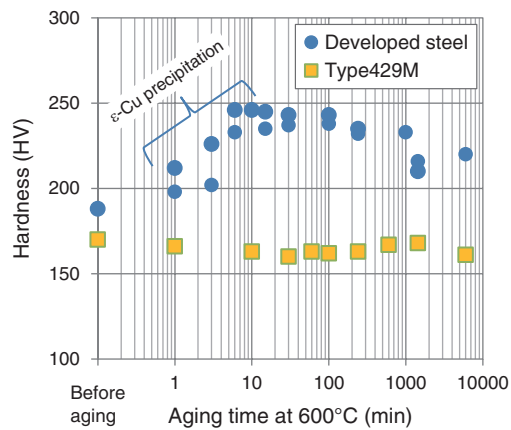


Fig. 6 Change in hardness at 600°C

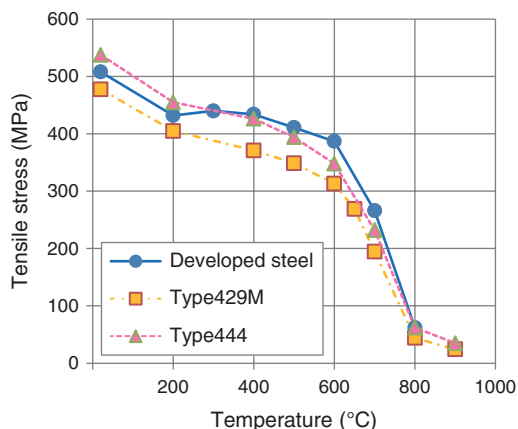


Fig. 7 Result of high-temperature tensile test

compared to the high-strength ferritic stainless steel Type444.

Figure 8 shows the results of the completely reversed bending high cycle (10^7 times) fatigue test at 800°C. The fatigue limit of the developed material improved by 20% or more over that of Type429M, and the material retained tensile strength that was equal to or better than that of Type444.

Figure 9 shows the results of the thermal fatigue test conducted under conditions in which cooling and heating cycles from 100°C to 700°C were added. The thermal fatigue life of the developed material was 40% longer than that of Type429M, and it retained a lifetime equal to or better than that of Type444.

4.2. Oxidation Resistance

Because stainless steel suddenly oxidizes when a limit temperature is exceeded⁽⁸⁾, that temperature is called the oxidation-resistant marginal temperature, and it determines the limits for use of a material. Figure 10 shows the oxidation-resistant marginal temperature of various materials in the atmosphere. Because the oxidation-resistant marginal temperature of the developed material is 950°C, it is equal to or higher than that of Type429M, and the material exhibits sufficient oxidation resistance for use in a catalytic converter.

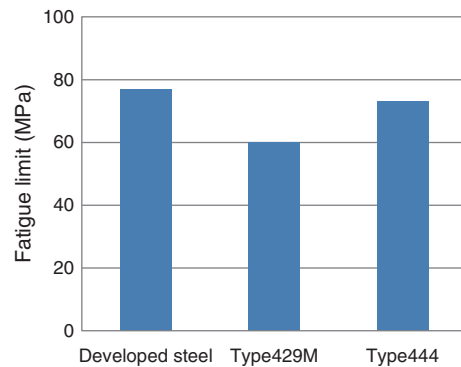


Fig. 8 Fatigue limit at 800°C

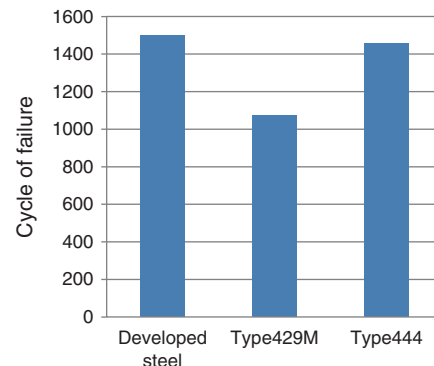


Fig. 9 Result of thermal fatigue test

Table 2 Pitting resistance equivalent (*PRE*)

	Cr	Mo	<i>PRE</i>
Developed steel	17	0	17
Type429M	14	0	14
Type409L	11	0	11
Type444	18	2	25

PRE = Cr + 3.3Mo (mass%)

4.3. Corrosion Resistance

As stated in chapter 3, the corrosion resistance of stainless steel is known to be correlated with *PRE*. As *PRE* increases, corrosion resistance improves. Table 2 shows the *PRE* of various materials for exhaust systems. The *PRE* of the developed material is higher than it is for Type429M, so superior corrosion resistance is expected. An evaluation of corrosion resistance was performed using the pitting potential method specified in JIS G 0577, and the pitting potential measurement results for various materials are shown in Fig. 11. Corrosion resistance increases as pitting potential increases. The pitting potential of the developed material is equal to or greater than that of Type429M, and the material demonstrated sufficient corrosion resistance for use in a catalytic converter.

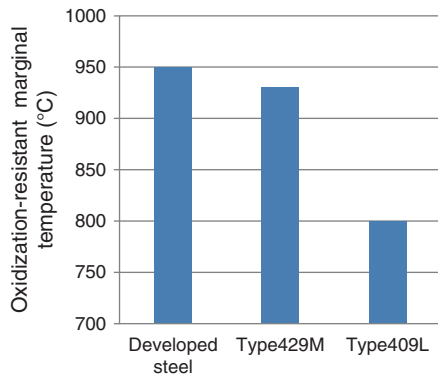


Fig. 10 Oxidation-resistant marginal temperature

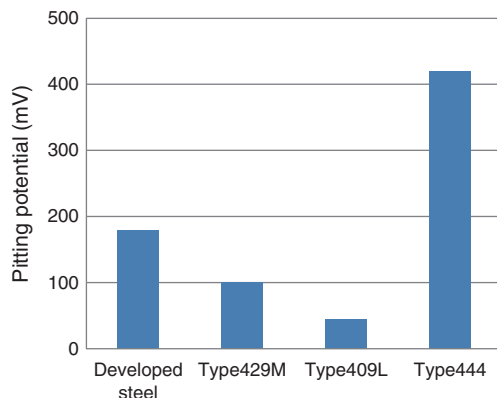


Fig. 11 Result of pitting potential measurement

Table 3 Test result of *r*-value

	Thickness (mm)	<i>r</i> -value			
		<i>r</i> ₀	<i>r</i> ₄₅	<i>r</i> ₉₀	<i>r</i> _m
Developed steel	2.0	1.38	1.23	1.98	1.46
	1.5	1.74	1.26	2.36	1.65
Type429M	2.0	1.15	0.88	1.49	1.10
	1.5	1.30	0.96	1.85	1.27
Type444	2.0	1.01	0.96	1.29	1.06
	1.5	1.30	0.87	1.69	1.18

$$r_m = (r_0 + r_{90} + 2r_{45})/4$$

4.4. Workability

r-value measurement results are shown in Table 3. *r*₀, *r*₄₅, and *r*₉₀ are the angles 0°, 45°, and 90°, respectively, with respect to the rolling direction. *r*_m is the mean *r*-value. The results of the test are expressed in Eq. (3).

$$r_m = (r_0 + r_{90} + 2r_{45})/4 \quad (3)$$

When C and N are reduced and comparisons are made at the same plate thickness, the *r*-value of the developed material is higher than that of Type429M. Also, because we were able to decrease the plate thickness from 2.0 mm to 1.5 mm as a result of increasing the strength of the material, we achieved an even higher *r*-value. Utilizing this high *r*-value, integral press-forming of one part of the converter (Fig. 12, Part A) was investigated. Figure 13 shows the results of the press-forming test of Part A. Although the

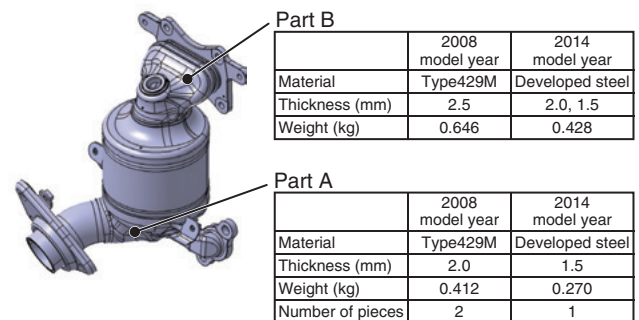


Fig. 12 2014 model year FIT catalytic converter

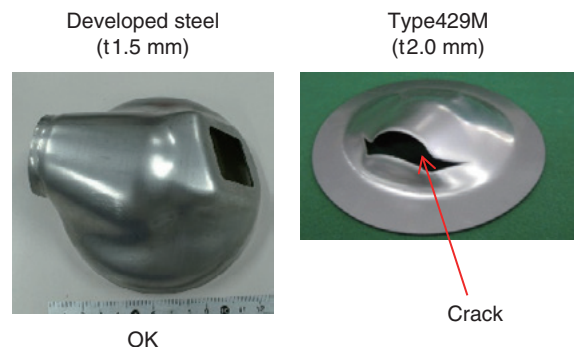


Fig. 13 Press-forming result of part A

part breaks during press-forming with Type429M, we were able to press-form the part when using the developed material. Because Type429M cannot be used to perform integral press-forming of this part, conventionally it had been produced by welding together a 2-piece press part. However, using the developed material, it was possible to perform integral press-forming of the part to replace it with a one-piece press part.

During complicated press-forming, materials are locally extended, decreasing the plate thickness. However, with a higher rate of decrease, the plate thickness becomes thin locally, which is not desirable from the perspective of endurance reliability and so on. Therefore, it is preferable to minimize the rate of decrease of the plate thickness as much as possible. Figure 14 shows the measurement results of the plate thickness decrease rate after the press-forming of Part B. The value of the plate thickness decrease rate is obtained using Eq. (4).

$$D = (t_{p0} - t_{p1}) / t_{p0} \times 100 (\%) \quad (4)$$

D : Plate thickness decrease rate

t_{p0} , t_{p1} : Plate thickness before and after press-forming

Both the developed material and Type429M are capable of forming Part B. However, the developed material had the lowest plate thickness decrease rate (plate thickness 2.0 mm). The second-lowest was Type429M (plate thickness 2.0 mm), and Type429M (plate thickness 2.5 mm) was the highest. The plate thickness decrease rate following press-forming is correlated to the r -value of a material. We observed that the high r -value of the developed material minimized the plate thickness decrease rate during press-forming.

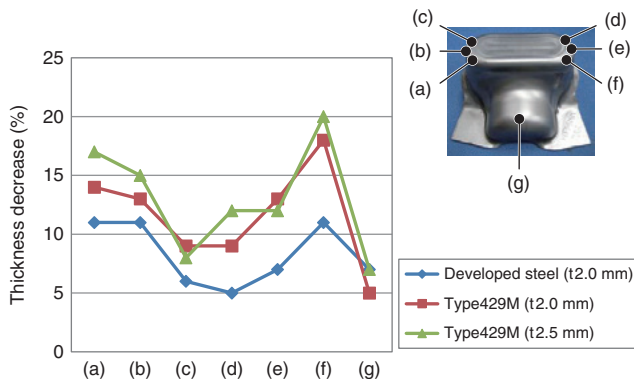


Fig. 14 Thickness decrease after part B press-forming

5. Weight Reduction Effect

Plate thickness was decreased by 20% or more by using the developed material in two parts of the catalytic converter (part A and part B) for the 2014 model year FIT shown in Fig. 12. Integrated press-forming was also

performed for Part A. As a result, the weight of the parts where the material was used was reduced by a total of 0.36 kg.

Also, the weight reduction of material while simultaneously cutting costs was achieved by doing the following: developing a high-strength ferritic stainless steel that did not contain Mo, decreasing the quantity of material used by decreasing plate thickness, and reducing the press-molding cost and decreasing welded parts by integrating two pieces into one.

6. Conclusion

HSS430CU, which has superior strength at elevated temperatures and excellent press-forming properties, thereby decreasing the weight and cost of the catalytic converter for the 2014 model year FIT, has been developed.

- (1) The high-strength ferritic stainless steel HSS430CU demonstrated good workability, as a result of Cu being incorporated into solid solution during forming. This material also exhibited strength at elevated temperatures following vehicle installation, as a result of fine ϵ -Cu precipitation caused by thermal energy from exhaust gas.
- (2) The weight of the catalytic converter was reduced by decreased plate thickness with application of high-strength material and integrated press-forming with increased r -value.
- (3) The cost was reduced by not adding Mo and by performing integral press-forming of parts to reduce welded parts.

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