

Development of a Low Heat-Capacity Exhaust Manifold for SULEV

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ABSTRACT

A dual-wall exhaust manifold was developed that has low heat capacity in order to reduce the time taken to reach the catalyst activation temperature. An austenitic stainless steel with significantly improved high-temperature strength and oxidation resistance was developed by optimizing the composition design so that the inner tube could be made as thin as possible. The use of this material made it possible to increase the buckling strength at high temperatures and to make the inner tube wall 0.4 mm thick. In United States emission modes, a dual-wall exhaust manifold with an inner tube having a wall 0.4 mm thick is able to reach the catalyst light-off temperature 3 seconds faster than an ordinary single-wall manifold that is 2 mm thick. This achieved a reduction of approximately 22% in hydrocarbon (HC) emissions. The combined application of air-fuel ratio (A/F) control technology and catalyst technology together with the developed exhaust manifold made it possible to reduce the amount of precious metals used in an under-floor converter by approximately 20% compared to a 2001 model vehicle with SULEV specifications.

1. Introduction

In recent years, as the focus has remained on the effect automobiles have on the global environment, various local regulations are being enforced in many regions. One area of concern is air pollution due to exhaust emissions, and many countries are tackling the early creation of emissions regulations, such as those in California, USA. This has led to a continuing increase in commercial vehicles that meet ULEV (ultra low emission vehicle) and SULEV (super ultra low emission vehicle) regulations, which had been thought of as almost impossible to meet. In these engines, by combining

technologies for improved combustion, more precise air-fuel ratio control, improved catalytic converter conversion performance, and a modified exhaust system, there are fewer and fewer pollutants in exhaust emission^{(1), (2)}.

Among these technologies, the catalytic converter plays a large role in conversion. Therefore, accompanying the stronger exhaust emissions regulations, there has been an increase in the amount of precious metals used in catalytic converters. From the point of view of preserving precious metal resources, it is necessary to reduce the amount used, while at the same time it is increasingly necessary to develop technology to improve conversion performance.

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2. Development Aims

By giving the exhaust manifold thin walls and a low heat-capacity, it is possible to restrain the drop in exhaust gas temperature at engine start, and improve catalyst temperature rise properties. Working for these effects, a dual-wall exhaust manifold, with the inner tube 0.6 mm thick, was developed, and the emissions reduction effects reported^{(3), (4)}. Making the exhaust manifold a low heat-capacity manifold, in this way, is almost standard technology that contributes to reducing exhaust emissions. In order to contribute to further exhaust emission reductions and a reduction in the amount of precious metals used in catalytic converters, an even lower heat-capacity technology has been pursued. However, when using ferritic stainless steel, the conventional material, for the inner material, the strength limit is 0.6 mm. In the new development project, a high-strength austenitic stainless steel was developed, and with its application, a dual-wall exhaust manifold with an inner tube thickness of 0.4 mm was developed with the aim of thinner walls and lower heat capacity. The goals were a reduction in the amount of precious metals used and contributing towards meeting SULEV regulations.

3. Structure

Figure 1 shows the overall structure of the exhaust manifold developed in this project. Table 1 gives the applied material for each part. Both the tubes and chambers use a 4-1 connecting configuration, with an insulated dual-wall structure. Because the inner tube contributes greatly to heat-capacity, in order to aim for the absolutely lowest heat-capacity that doesn't compromise strength, it was made 0.4 mm thick using a newly developed material that is stronger than conventional materials.

A dual-wall structure was adopted for the chambers in order to give low heat capacity. The chamber is a structure that supports the exhaust gas flow downstream end through a

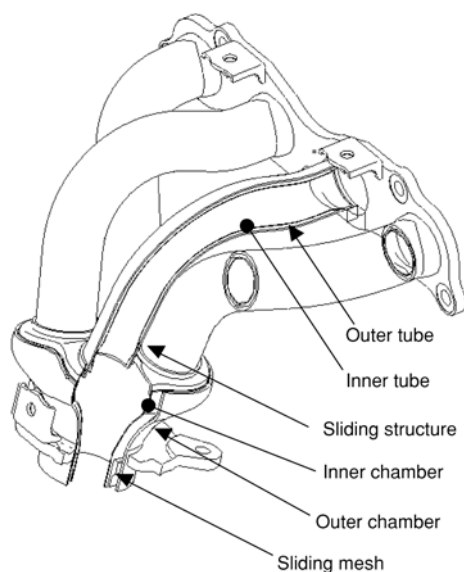


Fig. 1 Structure of exhaust manifold

Table 1 Applied material for each part

Part	Material	Thickness
Outer chamber	JIS SUH409L	2.0mm
Inner chamber	14Cr-Nb stainless steel	0.8mm
Outer tube	14Cr-Nb stainless steel	1.5mm
Inner tube	Developed stainless steel	0.4mm

stainless steel mesh. As for the inner chamber, because a slide stabilized by the mesh can be expected and buckling is difficult due to the shape, a conventionally used 0.8 mm ferritic stainless steel has been employed. With the above spec, in comparison with the conventional dual-wall exhaust manifold with an inner tube of 0.6 mm thick and inner chamber of 0.8 mm thick⁽³⁾, there is a heat-capacity reduction of 15%.

Next, this paper turns to two of the most important technological elements in this development project – inner tube material and slide structure.

4. Material

In the conventional dual-wall exhaust manifold, an example of the thinnest inner material would be the 0.6 mm thick ferritic stainless steel^{(3), (4)}. With these conventional parts, the main emphasis lay with durability, from the point of view of thermal fatigue⁽⁸⁾, and so ferritic stainless steel was used because it has little thermal expansion. However, in the development of dual-wall exhaust manifolds, technology has been established that avoids thermal fatigue through the use of a slide structure that absorbs thermal expansion^{(3), (4)}. This creates an environment where the use of austenitic stainless steel with large thermal expansion can be used. In addition, by giving the inner parts of the dual-wall exhaust manifold thinner walls, the main damage figuration has been changed to high temperature, high cycle fatigue from thermal fatigue⁽⁴⁾. In this development project, in order to aim for the greatest thin-walled low heat-capacity, and to achieve the target for an inner wall thickness of 0.4 mm, a study was made of the use of austenitic stainless steel which is very advanced in terms of high temperature, high cycle fatigue.

4.1. Material Concept

At high temperatures austenitic stainless steel is advanced in terms of strength. But because work hardening is great and because there is repeated application of normal to high temperature heat cycles that is peculiar to an automotive exhaust manifold, there are the following concerns in the use of austenitic stainless steel.

- (1) When strain induced martensite grows, work hardening is large, and machinability worsens. In addition, concerning strain induced martensite, reverse transformation occurs at approximately 800 °C, so deformations, etc., occur.
- (2) Due to repeated thermal expansion and shrinkage, the oxide film breaks away, and there is a drop in cyclic oxidation resistance.

Because of these issues, the development concept adopted was a stable austenitic stainless steel that could

withstand cyclic oxidation. Furthermore, a study was made to combine these characteristics with high-temperature strength so that it would be possible to have an inner thickness of 0.4 mm.

4.2. Composition Design

From the results of study of all properties, the decision was made to use 23Cr-11Ni-N-REM (rare earth metal element). The material concepts and the methods of achieving them based on this decision are shown in Fig. 2. Details of the various studies and their results are discussed below.

4.2.1. Stabilization of austenite structure

Generally, stainless steel structure can be estimated from the Ni equivalent: Ni_{eq} and Cr equivalent: Cr_{eq} calculated from the alloy components, using the Schaeffler diagram. However, when full consideration is given to N, the DeLong diagram shown in Fig. 3 is used⁽⁵⁾. In restricting strain induced martensite transformation, the basic idea is to avoid the martensite growth range (bottom left in Fig 2), and use the austenite range components. In addition, to avoid solidification cracking when welding, it is best to have composition design that gives a certain level of δ ferrite precipitation, meaning a composition design that tends to the ferrite.

4.2.2. Improvements to cyclic oxidation resistance

The reason austenitic stainless steel cyclic oxidation resistance is worse than that of ferritic stainless steel is that, due to repeated thermal expansion; the oxide film tends to break away, whereby protection against oxidation is lost. Accordingly, with improvements to oxide film adhesion, it is possible to improve resistance to cyclic oxidation.

A Ni-based alloy is generally used as an alloy with high resistance to cyclic oxidation. This has a smaller substrate thermal expansion than austenitic stainless steel, and because the difference with the oxidation layer's thermal expansion is small, there is no damage to the oxide film due to repeated thermal expansion. Because of this, it is possible to improve, to a certain extent, resistance to cyclic oxidation by the addition of a large quantity of Ni. However, because Ni is an expensive alloy element, it is not economical. In contrast, it is known that REMs precipitate at the grain boundary of the oxide film, improving adhesion^{(6), (7)}; due to this structure, it is also very effective as an additive even in minute amounts. Accordingly, it was decided to improve resistance to cyclic oxidation using the REM additive, which is economically superior to Ni additives.

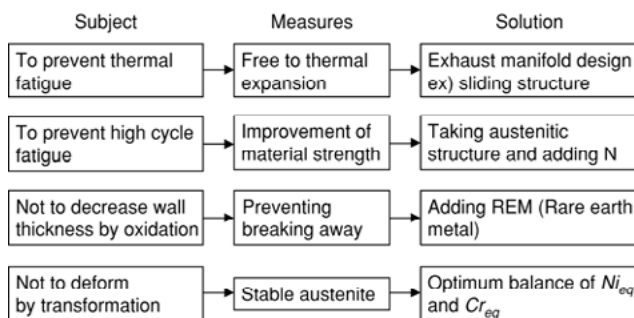


Fig. 2 Subject and solutions for thin inner wall exhaust manifold

4.2.3. Improvements to high temperature strength

As a hard structure that can maintain strength without the effects of re-crystallization at high temperatures, or of recovery, hardening is limited to solid solution hardening whereby solute atoms are a uniform solid solution on the substrate and harden, and to precipitation hardening whereby a foreign precipitated deposit is finely distributed on the substrate and hardened. Considering the requirements of automotive exhaust system materials and welding, and to it being un-tempered, the application of precipitation hardening is difficult to accomplish. Therefore, it is necessary to make effective use of solid solution hardening. Elements having good effect in solid solution hardening are invasive C and N⁽⁸⁾. However, under high temperature conditions, C forms the carbide $Cr_{23}C_6$ which is a cause of embrittlement. Therefore, it is not appropriate for maintaining long-term, stable strength in high temperatures. In addition, oxidation resistance also worsens because Cr is consumed in the above reaction. In comparison, it is difficult for N to form nitrides even under high temperature conditions, and it is possible to maintain long-term, stable strength even in high temperatures. In addition, because there is also a benefit in improving oxidation resistance⁽⁹⁾, it was decided to harden with an N additive.

4.3. General Properties of the Applied Composition

Table 2 gives the typical chemical composition of the developed stainless steel. Next, this paper will introduce the properties of these components.

4.3.1. Structural stability

Stainless steel is generally supplied to working in the annealed state. Figure 4 shows the metal structure changes due to cold working of the annealed material. As can be seen in the diagram, the initial austenite crystal grains deform, but strain induced martensite is not generated. The ferrite rates in each working level are less than the measurement lower limits when measured by the ferrite scope (Fischer MP30). From this it is known that it is a stable austenite structure.

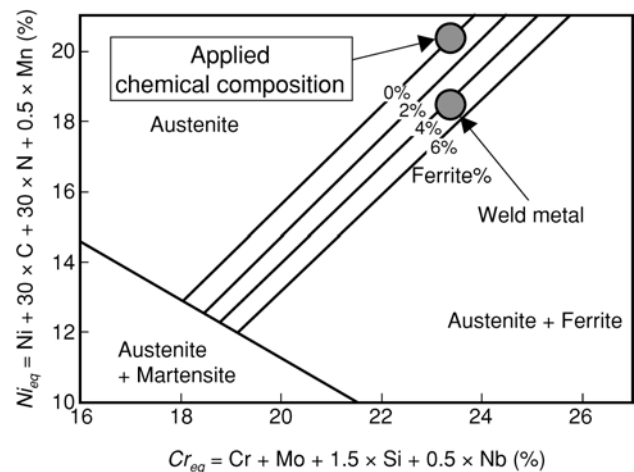


Fig. 3 DeLong diagram⁽⁵⁾

Table 2 Typical chemical composition of the developed stainless steel

(mass%)						
C	Si	Mn	Cr	Ni	N	REM
0.07	0.31	0.79	22.86	11.68	0.20	0.03

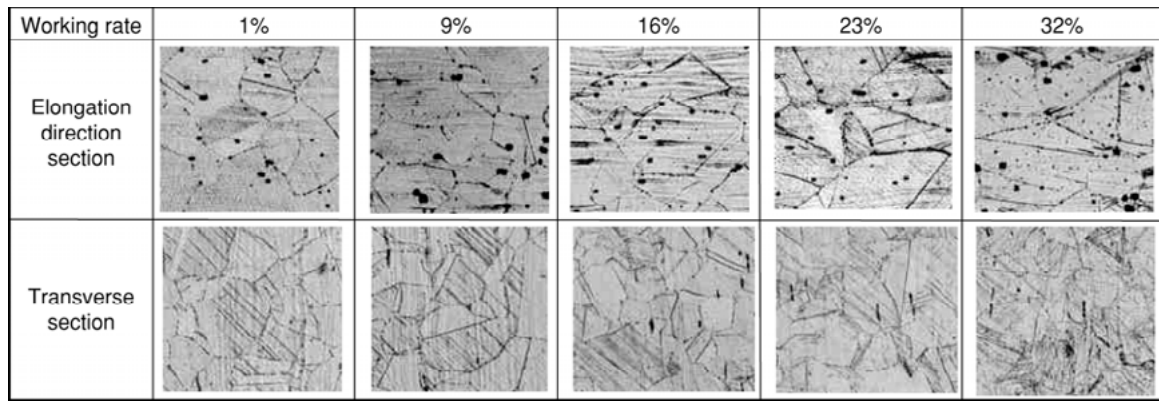


Fig. 4 Change of metal structure by cold working

The TIG weld metal structure is shown in Fig. 5; it is clear that it is an austenite dendrite crystal. In order to avoid weld cracking in austenitic stainless steel weld metal, it is effective to have precipitation of 5% ferrite⁽⁵⁾. Measuring the ferrite rate of weld metal using a ferrite scope, it is stable at approximately 5%. Analyzing the weld metal's nitrogen, it is 0.14%, and the Ni equivalent becomes $Ni_{eq} = 18.38$, so as shown in Fig. 3, ferrite rate is approximately 5%. In this way, by reducing the amount of nitrogen according to the weld, the ferrite rate can reach its optimum value.

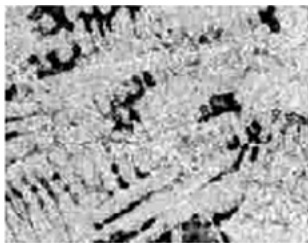


Fig. 5 Structure of weld metal

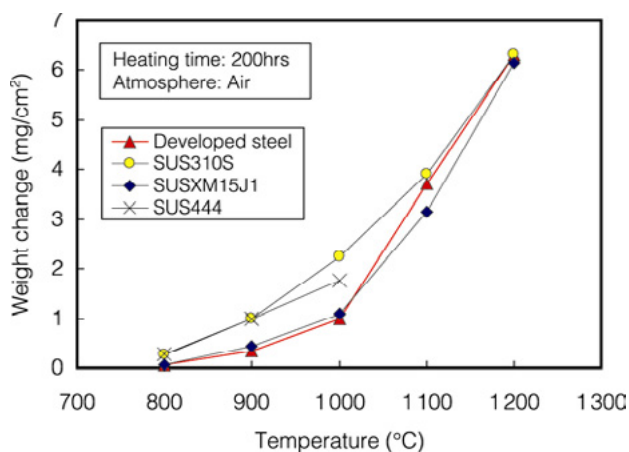


Fig. 6 Weight change by continuous heating

4.3.2. Oxidation resistance

Figure 6 shows the results of the continuous oxidation test carried out at various temperatures in the air. In continuous oxidation, weight increases due to oxide film growth, and the material that has the least growth is superior in continuous oxidation resistance. From these results it was learned that the developed material has resistance to continuous oxidation that is equal to or better than conventional austenitic stainless steel.

Figure 7 shows the weight changes due to cyclic oxidation in the case of heat cycle applied in air. In this type of cyclic oxidation, a weight reduction can be seen due to the separation of the oxide film, and the material that has the least reduction is superior in cyclic oxidation resistance. From these results it was learned that the developed material has no reduction in weight, so there is almost no break away of oxide film, meaning that it is superior in resistance to cyclic oxidation to conventional stainless steel.

4.3.3. High temperature strength

Among the various high temperature strength properties, Fig. 8 shows proof stress. The developed material achieved strength, at 800 °C, approximately three times that of SUS444, which has the best high-temperature strength of the ferritic stainless steels. In addition, it is 1.2-1.5 times stronger in comparison with conventional austenitic stainless steel.

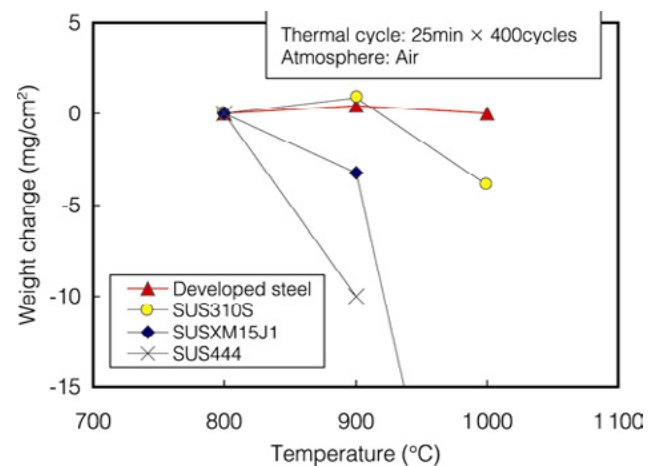


Fig. 7 Weight change by thermal cycles

5. Study of Port Structure

5.1. Evaluation of Buckling Strength in the Dual-wall Tube

In the dual-wall structure, the inner tube comes directly in contact with the exhaust gas and has a higher temperature than the outer tube. Therefore, the inner tube has relative

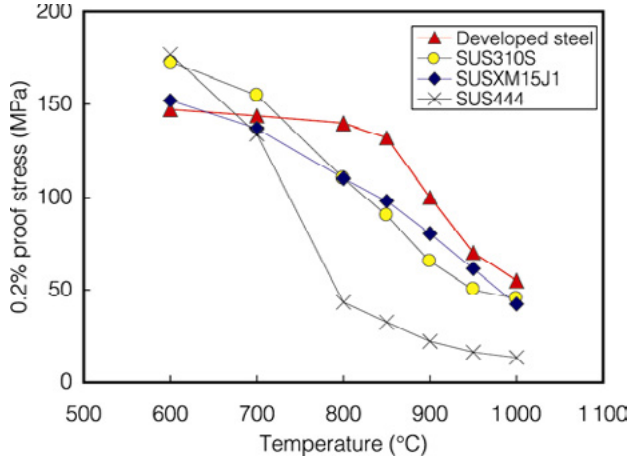


Fig. 8 Proof stress under high temperature

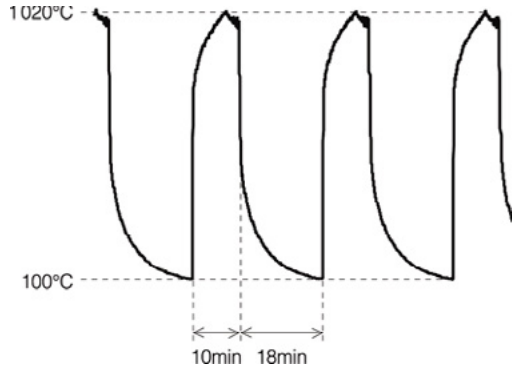


Fig. 9 Thermal cycle pattern for buckling test

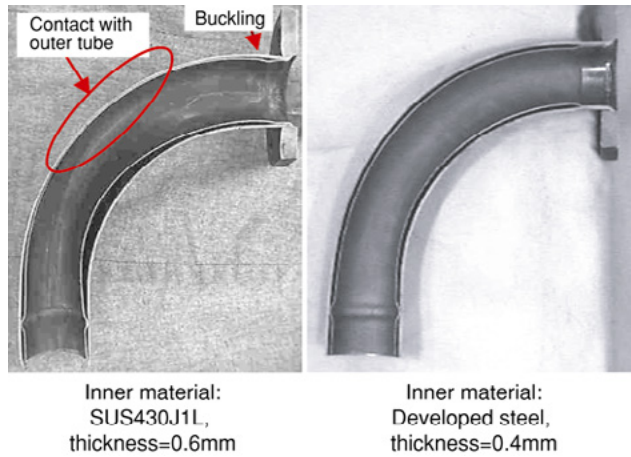


Fig. 10 Buckling deformation of the inner tube after thermal cycles

expansion to the outer tube so that when the inner tube high temperature yield strength is insufficient buckling deformation occurs. Therefore, a comparison of conventional material and newly developed material buckling strength was made using an exhaust gas simulation tester. The exhaust gas temperature was 1,020 °C, higher than the actual engine, for the acceleration test. The test was the application of 40 thermal cycles, as shown in Fig. 9, and then inner tube buckling deformation was monitored. Figure 10 shows the results of the buckling test. With conventional ferritic stainless steel, even at 0.6 mm thickness, there is buckling deformation, the inner and outer tubes adhere to each other, and it is not possible to maintain the insulated dual-wall structure, which is the actual purpose. In comparison, with the newly developed material, even at 0.4 mm thickness, there is no buckling deformation.

In order to analyze this buckling deformation behavior, relative thermal expansion was measured as shown in Fig. 11. Figure 12 shows a typical example of relative thermal expansion curve obtained through this test. In this case, the theoretical relative thermal expansion value was calculated using the following equation.

$$\Delta L_{cal} = \alpha_{in} L_{in} \Delta T_{in} - \alpha_{out} L_{out} \Delta T_{out} \quad (1)$$

ΔL_{cal} : Calculated relative thermal expansion

α_{out} : Linear thermal expansion coefficient of outer material

α_{in} : Linear thermal expansion coefficient of inner material

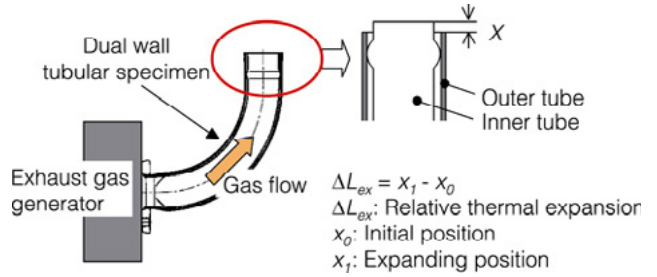


Fig. 11 Test method to measure the relative thermal expansion of inner tube

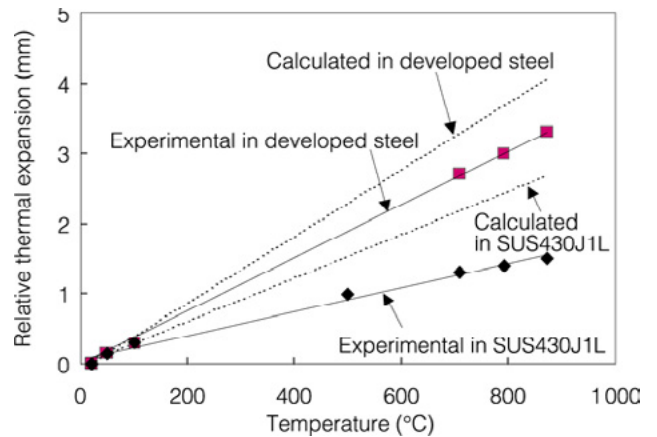


Fig. 12 Thermal expansion behavior

- L_{out} : Length of outer tube
 L_{in} : Length of inner tube
 ΔT_{out} : Temperature vary of outer tube
 ΔT_{in} : Temperature vary of inner tube

As can be seen from these results, with the ferritic stainless steel SUS430J1L, relative thermal expansion amount is small, but dissociation from the calculated value is large, and it is clear that thermal expansion restraint is large. In contrast, with the newly developed steel – an austenitic stainless steel – the relative thermal expansion is large, but dissociation from the calculated value is small, and it is clear that thermal expansion restraint is small. Examining these differences, it is thought that when the thermal stress generated by the restraint exceeds the material's proof stress, it is a cause of buckling. Accordingly, when used in parts with this sort of structure, it is necessary to consider restraint levels in the design parameters.

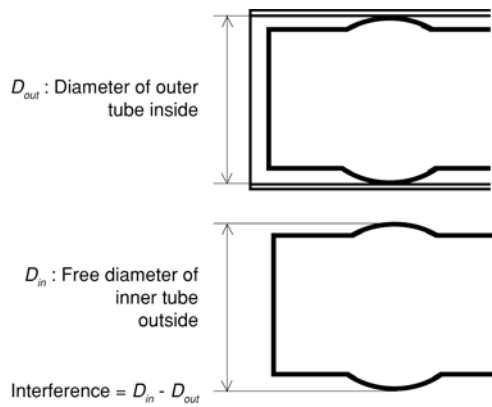


Fig. 13 Structure of sliding port

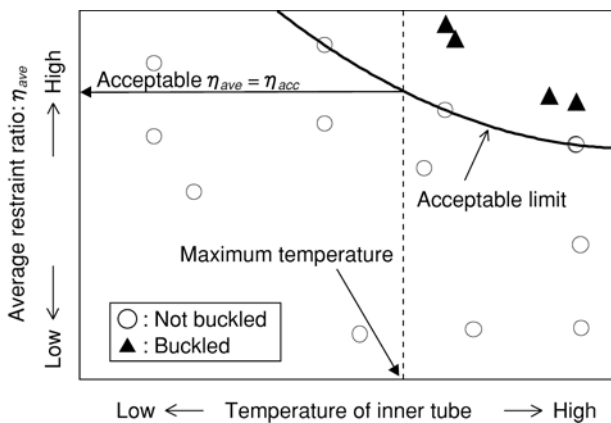


Fig. 14 Acceptable average restraint ratio

5.2. Quantitative Evaluation of Buckling Limits

As for thermal fatigue in exhaust system, it has previously been verified that restraint ratio is the optimum evaluation parameter⁽¹⁰⁾. Enlarging on this, as a parameter to quantitatively evaluate buckling limits against thermal expansion, average restraint ratio over tube length η_{ave} is defined.

$$\eta_{ave} = \frac{\Delta L_{cal} - \Delta L_{ex}}{\Delta L_{cal}} \quad (2)$$

η_{ave} : Average restraint ratio

ΔL_{ex} : Experimental relative thermal expansion

Average restraint ratio depends on the interference of the slide part. Here, interference is defined as illustrated in Fig. 13. From buckling generation state when average restraint ratio and temperature are changed, the buckling limit graph when the newly developed material is used is as shown in Fig. 14.

5.3. Design of Slide Structure

Exhaust gas flow upstream end of inner tube and outer tube is welded to the flange on the cylinder head side. The downstream end, as shown in Fig. 13, is a sliding structure. Here, setting the exhaust manifold usage design temperature makes it possible to determine acceptable average restraint ratio η_{acc} , from Fig. 14. In order to guarantee inner tube buckling strength, it is necessary to set the interference so the sliding structure slides with no more than the average restraint ratio η_{acc} . Examining the relationship between this interference and average restraint ratio using actual shape samples with three bending points, Fig. 15 shows the test results according to the behavior analysis shown in Fig. 11. From this relationship, in order to keep average restraint ratio within η_{acc} , it is clear that slide part interference should be kept at no more than I_{max} , and this was set as the design maximum interference.

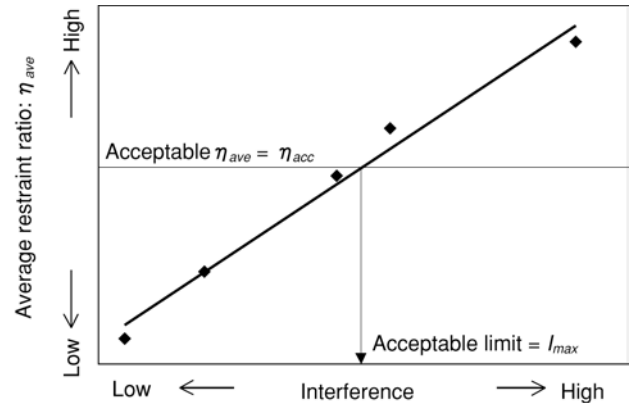


Fig. 15 Relationship of interference and average restraint ratio

6. Part Performance

A comparative test was carried out, using the newly developed exhaust manifold and a 2 mm thick, conventional, single-wall one. Table 3 gives the specifications of each exhaust manifold.

6.1. Emission Performance

6.1.1. Temperature rise properties

The differences in catalytic converter temperature rise properties in US FTP (federal test procedure) cycle at engine start are shown in Fig. 16. After start, the catalyst temperature difference gradually appears, and 20 seconds after start there is a 40 °C temperature difference, and the catalyst's light-off temperature of 400 °C is achieved 3

Table 3 Specification of the exhaust manifold for comparison test

	Tube		Chamber	
	Outer	Inner	Outer	Inner
Conventional	2mm	—	2mm	2mm
Developed	1.5mm	0.4mm	2mm	0.8mm

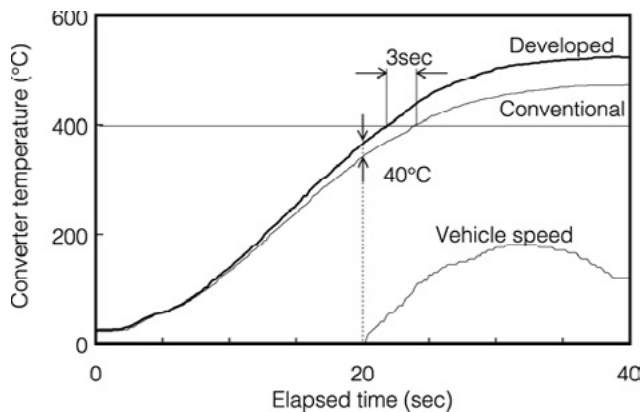


Fig. 16 Converter heat-up behavior on FTP cycle

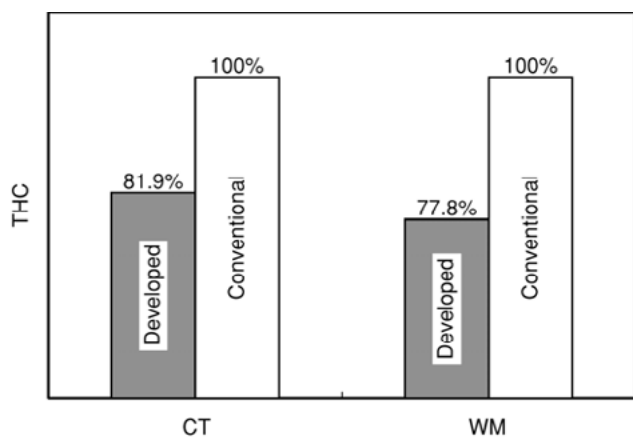


Fig. 17 Effect for emission decrease

seconds earlier with the newly developed part. Due to this effect, by using the newly developed exhaust manifold, it is possible to reduce emissions that are discharged before light off.

6.1.2. Level of emissions achieved

In order to examine the effect on emissions, as a representative value Fig. 17 shows the differences in HC emission amount. By using the newly developed exhaust manifold, with its ability to have early activation of the catalyst at cold start, there is a large effect in reducing emissions at CT (cold transient) – a reduction of approximately 18%. In addition, even with the mode total weighted mean value WM, there is a 22% reduction. In the same way, there is a 10% reduction in NO_x, and a 12% reduction in CO. It is possible to verify a large emission reducing effect.

6.2. Noise Properties

Figure 18 shows a comparison of the differences in noise level due to differences in exhaust manifolds. The newly developed exhaust manifold shows a slight worsening in the high frequency range in comparison with the conventional single-wall product; however in the low frequency range it is superior, and overall it is roughly equivalent. In general, the dual-wall exhaust manifold has worse noise properties than the single-walled one⁽³⁾. But, it is believed that with this newly developed manifold, because the inner tube is a completely cylindrical shape, stiffness is comparatively high and there is little noise property worsening.

7. Summary

Development of an exhaust manifold with an inner tube 0.4 mm thick, working to make it as thin-walled and low heat-capacity as possible, was a success. In combination with air-fuel ratio control technology and catalyst technology, it was possible to reduce by approximately 20% the amount of precious metals used in the under-floor converters, in comparison with the 2001 model SULEV spec vehicle. As a result of this development project, the following facts have become clear.

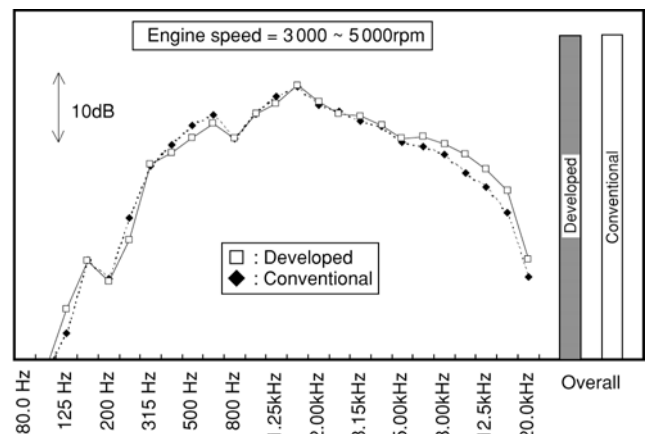


Fig. 18 Comparison of sound pressure level

- (1) In order to actualize thinner walls than conventional exhaust manifold for the inner material of the dual-wall, a highly heat resistant stainless steel was developed that had improved high temperature strength and oxidation resistance, by N additives, REM additives, and improving Ni_{eq} - Cr_{eq} balance.
- (2) When using the newly developed highly heat resistant stainless steel for the inner tube of a dual-wall exhaust manifold, it was verified, in the unit thermal cycle test, that there is greater strength against buckling deformation than with the conventional material.
- (3) The acceptable average restraint ratio was determined according to the buckling evaluation using the unit thermal cycle test. Quantitative evaluation is possible using this acceptable value, and even with a thickness of 0.4 mm, it is possible to have a design that satisfies durability requirements.
- (4) The dual-wall exhaust manifold with the inner tube 0.4 mm thick can reach catalyst light off, in the FTP mode, three seconds earlier than the conventional one.
- (5) The dual-wall exhaust manifold with the inner tube 0.4 mm thick has a radiated noise level equivalent to that of the exhaust manifold with a thickness of 2 mm (single wall).

The exhaust manifold developed in this project has begun mass production in 2002, and is fitted to the 2003 Accord series, the US SULEV spec vehicle.

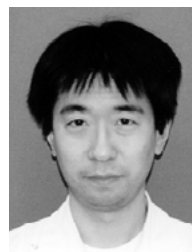
8. Acknowledgments

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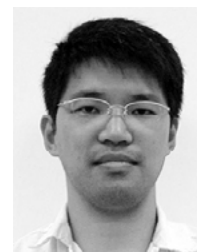
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