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Development of Heat-Resistant Metal Support for Catalytic Converter of Automobile Exhaust Gas

Atsuhiko Imai*1
Takashi Tanaka*2
Shigeru Ogawa*2
Yutaka Satano*4
Mikio Yamanaka*2
Yasushi Ishikawa*2
Masao Yashiro*3
Masahiko Ogata*1

Abstract:

A metal support of the manifold catalytic converter type was developed for an automobile exhaust gas cleaning catalyst to be installed immediately below the exhaust manifold of gasoline engine. The manifold catalytic converter is exposed to the cycled heat of hot and turbulent exhaust gas in the manifold, and therefore must have high heat resistance and rigid support structure. The metal support developed by Nippon Steel Corporation is characteristic in that a few honeycomb core outer layers are axially brazed over the entire length for reinforcement and that the honeycomb core is welded only on the exhaust gas inlet side as an asymmetrically brazed structure. The brazed metal support structure is extremely durable and has various advantages over the conventional ceramic support, including improved exhaust gas cleaning performance.

1. Introduction

Amid mounting calls for the protection of the global environment in recent years, abolishing the use of chlorofluorocarbons (CFCs) and tightening the control of automobile exhaust gas emissions have been energetically taken up as urgent measures against the depletion of the ozone layer. As the LEV regulation is being enforced in California of the United States and diesel engine exhaust gas regulations are being strengthened, technology development for improving the cleaning of automobile exhaust gas is now an issue of paramount importance. The demand for increased engine output, on the other hand, makes it essential to reduce the exhaust gas pressure loss. Reducing the pressure loss through the catalyst support that accounts for a large percentage of the entire exhaust system pressure loss is of particular importance. Against this background, metal supports are spotlighted as automobile exhaust gas cleaning catalyst supports[1,2].

The metal support has a honeycomb core made of stainless steel foils of high heat resistance. It features a lower exhaust gas pressure loss, higher heat resistance, smaller size, and easier installation than the conventional ceramic support. The catalytic converter located just below the engine exhaust manifold (hereinafter referred to as the manifold catalytic converter) allows the exhaust gas cleaning three-way catalyst to quickly reach the starting temperature for the catalytic reaction, and excels in exhaust gas cleaning performance. Recently the exhaust gas temperature is rising as the air-to-fuel ratio is increased to meet the requirements for greater engine output and better fuel economy. The

*1 New Materials Divisions Group
*2 Technical Development Bureau
*3 Nagoya Works
*4 Hikari Works

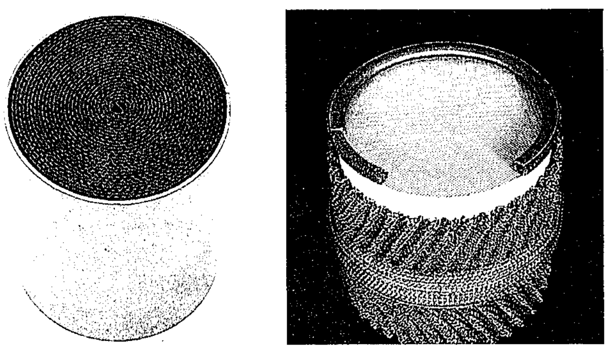
increasing exhaust gas temperature calls for manifold catalytic converters of increased heat resistance[3].

Nippon Steel carried out development work on a metal support foil material, brazed metal support structure capable of withstanding the service environment immediately below the exhaust manifold, and metal support manufacturing process. As a result, the company has established an integrated production technology covering the whole process from the material to product support. This report describes the progress of development, and the results of investigation made into the internal temperature distribution of the metal support by engine thermal shock tests, and into the durability of its brazed structure by failure analyses.

2. Advantages of Metal Support

Photo 1 shows the appearance of a metal support and a ceramic support (cordierite). The metal support does not need the retainer, wire net, and exhaust gas seal that are indispensable for the ceramic support. The honeycomb core of the metal support is made of ferritic stainless steel foils with high oxidation resistance, and is composed of spiral rolled flat and corrugated foils. **Table 1** compares the properties of the metal support and the ceramic support[4].

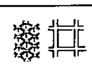
The metal support generally has the following advantages over the ceramic support:



(a) Metal support (b) Ceramic support

Photo 1 Appearance of metal support and ceramic support

Table 1 Comparison in properties of metal support and ceramic support

		Metal support	Ceramic support
Material property	Honeycomb material	Ferritic stainless steel (20Cr-5Al-Ti-Ln)	Cordierite ($2MgO$-$2Al_2O_3$-$5SiO_2$)
	Thickness (μm)	50	170
	Specific heat (kJ/kg°C)	0.5	1.0
	Coefficient of thermal expansion (W/m°C)	14	1
Shape property	Cell shape		
	Cell counts (cells/in^2)	400	400
	Porosity (%)	90	75
	Geometric surface area (cm^2/cm^3)	32	27

(1) The cell wall thickness of the metal support is about 50 μm which is one-third of that of the ceramic support. This sharply reduces the exhaust gas pressure loss of the engine.

(2) The porosity of the cells is improved from 75% to 90%, and the geometrical surface area per unit volume is thus increased. In addition, absence of retaining hardware means smaller size and simpler construction, which facilitates the ease of installation around the engine.

(3) The metal support has such high heat resistance that it can be installed right below the exhaust manifold. The time for the three-way catalyst to reach the catalytic reaction start temperature can thus be shortened to improve the exhaust gas cleaning performance.

3. Development of Heat-resistant Metal Support

(1) Goal of development

Prior to the metal support development for installation just below the exhaust manifold, Nippon Steel worked on the development of a honeycomb core material and support structure, taking into consideration the probable support service temperature, mounting conditions, and other factors involved. The material of the honeycomb core must withstand the engine exhaust temperature of over 850°C and have excellent elevated-temperature mechanical properties as well as such workability that it can be easily rolled to a thickness of 50 μm. The support structure itself must be rigid enough to withstand a variety of tests, including the engine thermal shock test. The development of an appropriate honeycomb core-retaining system and brazed metal support structure was therefore a major challenge. **Photo 2** shows the metal support as installed on the engine.

(2) Material of metal support

The foil material of the honeycomb core is exposed to a punishing environment right below the exhaust manifold as previously noted. It therefore must have high heat resistance, elevated-temperature mechanical properties, and good workability into foils. After exhaustive efforts, Nippon Steel developed a ferritic stainless steel, designated YUS205M1 (20Cr-5Al-Ti-Ln), that meets all these property requirements[5]. As for the support jacket material, an extralow-carbon, nitrogen system 19Cr ferritic stainless steel YUS180 was selected in consideration of its corrosion resistance, weldability, and thermal expansion compatibility with the foil material.

(3) Investigation of internal temperature distribution of metal support

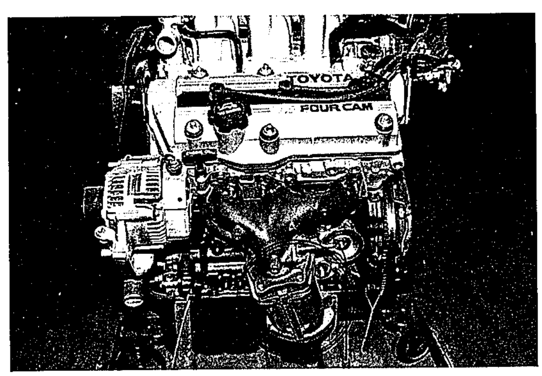


Photo 2 Metal support as installed on engine

The metal support of the manifold catalytic converter must have high structural durability to withstand the high-temperature heat cycles of the engine. The internal temperature distribution of the metal support in the engine thermal shock test was investigated to analyze the radial and axial thermal stresses acting on the metal support, and to determine the optimum brazed structure of the metal support.

Table 2 lists the conditions of the engine thermal shock test, and **Fig. 1** shows examples of heat patterns measured in the test. The temperature difference between the jacket of the metal support and the outermost layer of the honeycomb core reaches as high as 450°C and produces severe thermal stresses in the vicinity of the outermost layer of the honeycomb core. The radial temperature distribution of the metal support in the manifold catalytic converter is as shown in **Fig. 2. Fig. 3** shows the internal temperature distribution of the metal support in the manifold catalytic converter at 60 s after the start of the engine. The hot portions at the exhaust gas inlet are at the periphery of the honeycomb core. The temperature difference between the jacket of the metal support and the outermost layer of the honeycomb core is the largest in these peripheral areas. This uneven temperature distribution is difficult to avoid because the manifold catalytic converter is installed directly below the exhaust manifold where the exhaust gas is not straightened.

The above investigation of temperature distribution in the metal support points to the importance of minimizing the thermal stress and strain arising in the metal support from the heat cycles of the engine thermal shock test. Another important question is how to extend the metal support life until the honeycomb core separates from the jacket in a decisive failure of the metal support under the thermal fatigue that inevitably takes place in the honeycomb core.

(4) Retaining structure of metal support

There are principal basic methods for attaching the honeycomb core to the jacket of the metal support. The honeycomb core may be directly joined to the jacket as shown in **Fig. 4(a)**, or held in place by retainers as adopted for the ceramic support, as shown in **Fig. 4(b)**. The latter method secures the honeycomb core between the retainers and closes several millimeters of the

Table 2 Conditions of engine thermal shock test

Engine	2.0 L, V6 type
Exhaust gas temperature	150 to 850°C
Heat cycle	Heating: 10 min Cooling: 10 min
Standard number of cycles	900

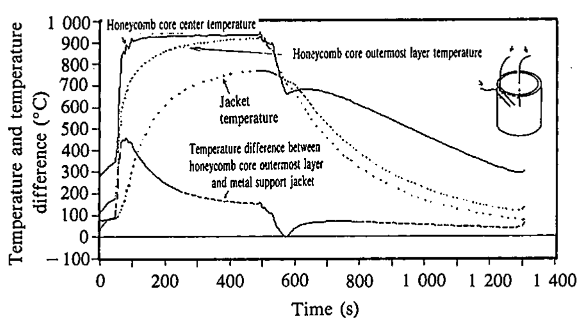


Fig. 1 Heat patterns measured in engine thermal shock test

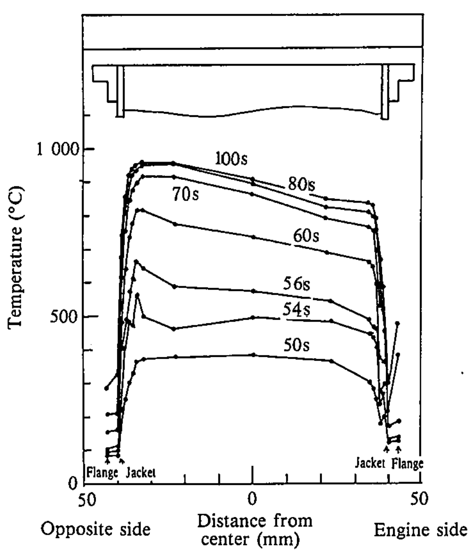


Fig. 2 Radial temperature distribution of metal support during heating

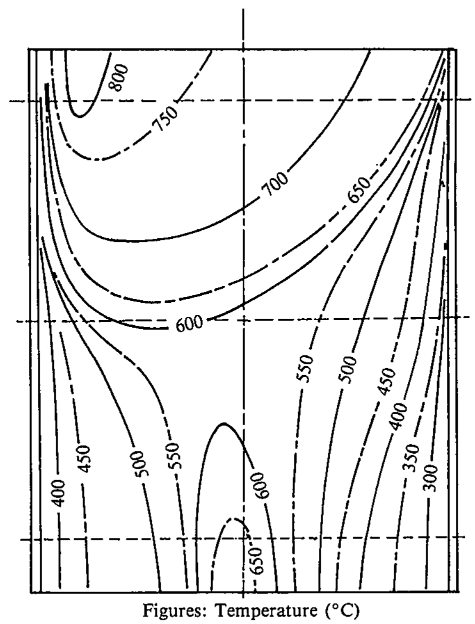


Fig. 3 Axial internal temperature distribution of metal support at 60 s after start of engine

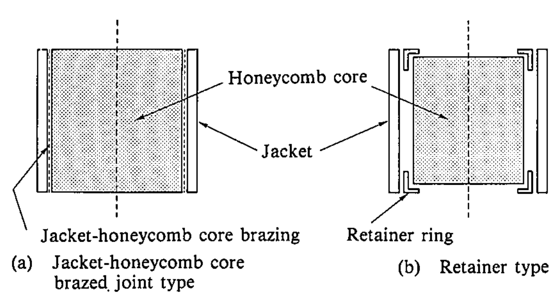


Fig. 4 Metal support honeycomb core securing structures

honeycomb core periphery. This method is disadvantageous because it does not fully utilize the catalyst and requires a large number of component parts. The former method of directly joining the honeycomb core to the jacket was therefore adopted. The metal support made by this method is advantageous over the ceramic support in terms of the efficiency of catalyst use and ease of installation. The direct joining of the jacket and honeycomb core into an integrate structure, however, makes it even more difficult to secure the structural durability, and the development of a brazed structure for relaxing thermal stress is an issue of utmost importance.

(5) Development of brazed metal support structure

Flat and corrugated stainless steel foils may be lapped and rolled in a spiral form or an S form[6]. Nippon Steel, considering the honeycomb core fabricability, adopted the spiral pattern as the basic honeycomb core rolling method and developed a brazed metal support structure with excellent durability.

The structure A in which the honeycomb core is brazed at both ends and is brazed to the jacket at the axial center as shown in **Fig. 5** was studied as the basic structure. When this structure was subjected to the engine thermal shock test, the jacket-honeycomb core brazed joint failed and easily caused the separation of the honeycomb core from the jacket. The failure is schematically illustrated in **Fig. 6**. The outermost layer that secures the honeycomb core to the jacket is broken at the ends of the jacket-honeycomb core brazed joint, resulting in the separation of the honeycomb core from the jacket.

In the heat cycles of the engine thermal shock test, the temperature difference between the outermost layer of the honeycomb core and the jacket is the largest as shown in **Fig. 1**, and the thermal stress generation is the highest in the three outermost layers of the honeycomb core. The thermal strain resulting from the difference in the coefficient of thermal expansion between the jacket material and the foil material and from the temperature distribution in the honeycomb core is calculated to be about 0.6%. This value is much larger than stainless steel's elastic strain limit of 0.2% in the vicinity of 500°C, and clearly indicates the plastic deformation of the outermost layer of the honeycomb core. Moreover, thermal stress is concentrated at the ends of the jacket-honeycomb core brazed joint and further accelerates the plastic deformation of the outermost honeycomb core layer. With the structure A where the honeycomb core is secured to the jacket by the outermost layer alone, the outermost layer is easily broken, making it impossible to assure the durability of the metal support.

(6) Reinforced outer layers for improved life

The failure of the outermost layer of the honeycomb core is difficult to prevent under such severe heat cycles as previously described. To improve the durability of the metal support, efforts must be centered on extending the length of time from crack initiation in the jacket-honeycomb core brazed joint until honeycomb core separation from the jacket. How to meet this requirement will be studied next.

An alternative design was developed as structure B shown in **Fig. 7**, where a few outer layers of the honeycomb core (hereinafter referred to as reinforced outer layers) are brazed. Even if cracks should occur in the jacket-honeycomb core brazed joint, this structure retards the honeycomb core separation from the jacket until the cracks fully penetrate the reinforced outer layers.

When its durability was evaluated by the engine thermal shock test, the structure B lasted 900 cycles as shown in **Table 2**. After the test, the sample was disassembled and examined. It was confirmed as a result that the sample still had a long residual life until the honeycomb core separation from the jacket. In the engine thermal shock test, however, part of the honeycomb core protruded on the exhaust gas inlet side, as shown in **Photo 3**. With the lapse of test time, this protrusion led to the chipping

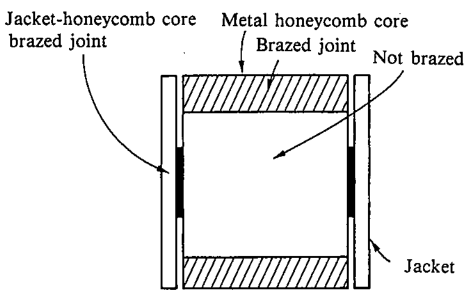


Fig. 5 Brazed metal support structure A (axial section)

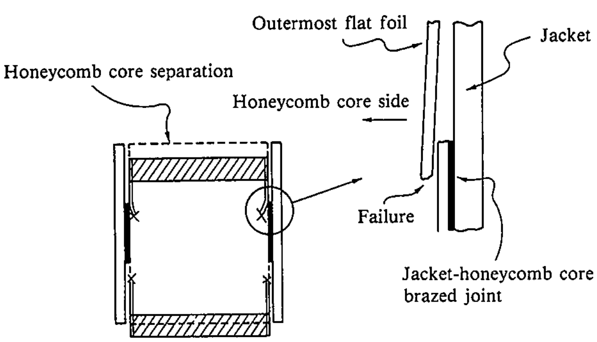


Fig. 6 Failure of structure A

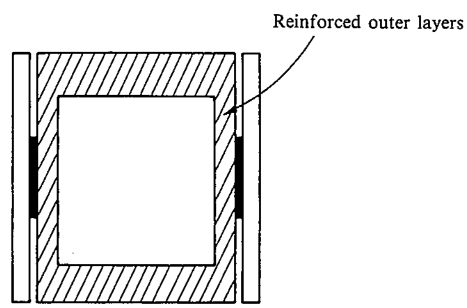


Fig. 7 Brazed structure B of metal support (axial section)

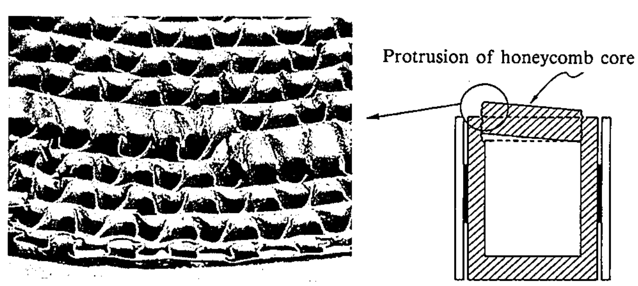


Photo 3 Protrusion of honeycomb core

and damage of the honeycomb core foils.

In this way, the structure B was proved to endure the honeycomb core separation from the jacket, but developed the problem of honeycomb core protrusion on the exhaust gas inlet side.

(7) Honeycomb core protrusion phenomenon

The honeycomb core protrusion phenomenon is such that corrugated foils at the boundaries of the reinforced outer layers of the honeycomb core break in the axial direction and cause the central honeycomb core to jut out in the exhaust gas inlet direction of the metal support. The cause of this phenomenon is described below.

Fig. 8 shows the tensile strength distribution and 0.2% offset yield strength distribution of the honeycomb core material on the axial section of the metal support at 60 s after the start of the engine, as estimated from the metal support temperature distribution shown in **Fig. 3** and from the elevated-temperature strength data of the honeycomb core material. The tensile strength of the honeycomb core material is about 40 to 50 kgf/mm^2 on the periphery of the exhaust gas outlet but is 10 kgf/mm^2 or less on the exhaust gas inlet side. The 0.2% offset yield strength exhibits similar tendencies. That is to say, heating produces a large strength variation in the honeycomb core in the axial direction and significantly lowers the strength of the honeycomb core on the exhaust gas inlet side.

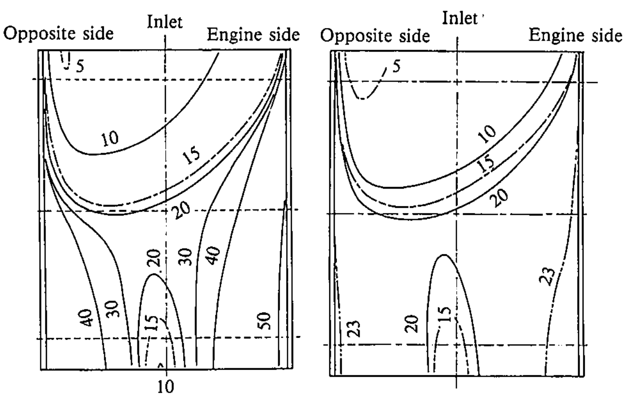
The temperature distribution shown in **Fig. 3** occurs in the metal support during heating. Thermal expansion in an amount corresponding to this temperature distribution occurs in the honeycomb core. This thermal expansion is large at the radial center and decreases toward the periphery of the honeycomb core. The periphery of the honeycomb core has brazed joints of reinforced outer layers and is restrained by the brazed joint of the honeycomb core with the jacket of high rigidity. These factors cause thermal strains to concentrate on the boundaries of reinforced outer layers and non-reinforced layers at the brazed ends of the honeycomb core. Since the honeycomb core is sharply reduced in strength at the exhaust gas inlet side as noted above, thermal strains concentrate on the exhaust gas inlet side. The progress of heat cycles is considered to cause the honeycomb foils to break and the radial center of the honeycomb core to protrude as shown in **Fig. 9**. The honeycomb foils in the protrusion-induced failure portions are lost by high-temperature high-cycle fatigue with increasing engine thermal shock test time.

(8) Development of asymmetrical brazed structure

Study was made of an alternative brazed structure capable of preventing the protrusion of the honeycomb core experienced with the structure B, and as a result, a new asymmetrical brazed structure C was developed, as shown in **Fig. 10**. With the new structure, the honeycomb core is brazed at the exhaust gas inlet, but not at the exhaust gas outlet. When the center of the honeycomb core thermally expands under the heat cycles of the engine, the honeycomb core can expand toward the exhaust gas outlet side, generating no thermal stresses in the axial direction. The protrusion of the honeycomb core can thus be prevented.

Since the protrusion phenomenon is believed to stem from shear stresses in the honeycomb core, shear stress analysis was made by the finite element method (FEM). The FEM assumed the honeycomb core to be an anisotropically elastic body and analyzed its elastic stress values accordingly. **Fig. 11** shows the maximum shear stress of the brazed joint on the exhaust gas inlet side of the honeycomb core. As expected, the maximum shear stress value turned out to be far smaller for the asymmetrical structure C than for the symmetrical structure B.

The structure C achieved the standard 900 cycles in the engine thermal shock test of the metal support, developed no protrusion problem, maintained the honeycomb core in a sound condition, provided sufficient service life, and performed best among the three types of brazed structures studied. Consequently, the brazed structure of the metal support for the manifold catalytic converter was finally decided to be of an asymmetrical design.



(a) Tensile strength distribution (kgf/mm^2)   (b) 0.2% offset yield strength distribution (kgf/mm^2)

Fig. 8 Tensile strength distribution and 0.2% offset yield strength distribution of metal support in axial direction (at 60 s after the start of engine)

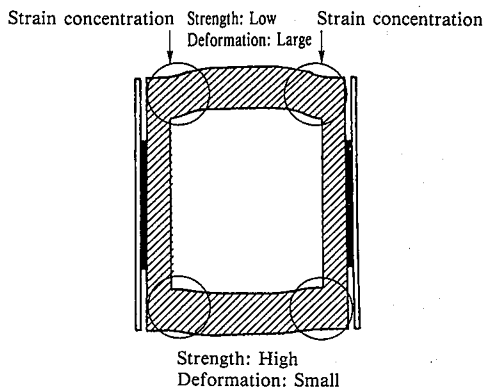


Fig. 9 Schematic illustration of honeycomb core protrusion

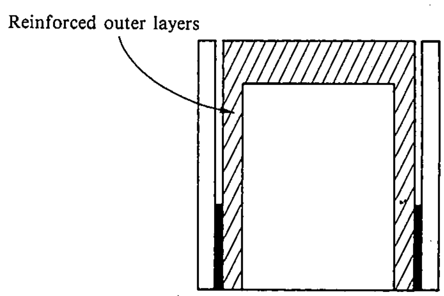


Fig. 10 Brazed structure C of metal support (axial section)

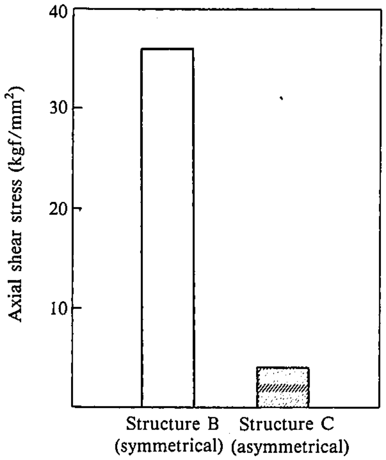


Fig. 11 Maximum axial shear stress as analyzed by FEM

4. Practical Application of Metal Support

A manifold catalytic converter metal support of the new brazed structure design was tested for the peeling-off of the catalyst coating and was proved to be as durable as the conventional ceramic support. After a variety of on-vehicle tests, including exhaust gas cleaning performance evaluation, it was installed on the Camry and Prominent models of Toyota Motor in July 1990. Its application was then expanded to the Soarer and other Toyota models.

Nippon Steel thereafter developed and commercialized metal supports for catalytic converters to be installed below the floor and in other locations on the automobile. Catalyst supports are subject to changes in temperature and other service conditions according to the on-vehicle location, which in turn has important bearings on the durability of the metal support. It is important, therefore, that the brazed structure of the metal support should be designed according to the on-vehicle location, be it immediately below the manifold or under the floor. There are various brazed structures worth trying, including the asymmetrical brazed structure discussed above.

5. Conclusions

The metal support of the catalytic converter type that can be mounted immediately below the exhaust manifold and can maximize the exhaust gas cleaning capability is exposed to an extremely severe service environment and therefore must have superior heat resistance and structural durability. A new metal support for the catalytic converter having the following features was developed:

(1) Retainers and other honeycomb core securing hardware are eliminated by brazing the honeycomb core to the jacket. This facilitates the effective utilization of the catalyst, and the size reduction and simplification of the catalytic converter.

(2) The brazing of a few outer layers of the honeycomb core significantly enhances the honeycomb core durability against separation from the jacket.

(3) The honeycomb core is brazed only on the exhaust gas inlet side. This asymmetrically brazed structure prevents the protrusion of the honeycomb core, and ensures an extremely durable metal support structure, including the reinforced outer layers.

Catalytic converters with the new metal support were first installed on the Camry and then on other Toyota models.

6. Acknowledgments

This development project was carried out by Nippon Steel jointly with Toyota Motor and Nippon Kinzoku. The authors gratefully acknowledge the cooperation of Manager Noda of Catalyst Design Dept. and Manager Ishikawa of Metallic Material Dept., Material Research & Development Div. I, Toyota Motor, and many other people in the commercialization of the new metal support for the catalytic converter.

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