

Development of Metal Honeycomb Substrate for Small Two-wheeled Vehicle Catalysts

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ABSTRACT

With the growing concern on protecting the global environment, exhaust emission regulations are becoming more stringent than ever, not only in advanced countries, but also in developing countries. To purify exhaust gases, the use of a metal-honeycomb catalyst is effective. A metal substrate for a honeycomb catalyst has been developed recently to use in small motorcycles used by a large number of people in developing countries. As part of this development, we have established a new assessment method for the CAE analysis of thermal stress and the hot-cold cycle and vibration-durability tests. Making full use of the said techniques, a low-cost metal-honeycomb substrate featuring vibration resistance and hot-cold cycle durability has been developed.

1. Introduction

In recent years, exhaust gas emission regulations have become increasingly stringent, mainly in advanced countries, and this has spurred moves to strengthen regulations in developing countries as well.

To clean exhaust gas, countermeasures such as the development of new engine technology and devices, different carburetor settings, and FI⁽¹⁾ are being adopted. However, along with demands for increasingly effective purification performance, catalysts using a honeycomb substrate (hereinafter called “honeycomb catalysts”) are becoming indispensable, and in fact are now commonly used in automobiles.

The majority of motorcycles manufactured are used as the main mode of transportation in developing countries, especially in India, China and the ASEAN region, and demand is great for an inexpensive honeycomb for installation on motorcycles intended for use in those countries. The component elements of a honeycomb

catalyst are divided into the catalyst coating, called a load, which cleans the exhaust gas, and the honeycomb substrate, which supports the coating. Of these elements, the inexpensive ceramic honeycomb substrate, which is the main type used in automobiles, is not practical in most models of motorcycles from the viewpoint of vibration strength, as they lack the characteristics required to withstand the vibration inherent in a motorcycle. For this reason, a metal honeycomb substrate is used for motorcycles, even though it is more expensive. To increase the range of application of the honeycomb catalysts for small motorcycles intended for use in developing countries, it is essential that the cost of the metal honeycomb substrate be reduced without loss of durability.

Through this research, metal honeycomb substrates for small motorcycles that were inexpensive but highly durable were developed. These substrates are shown in Fig. 1. This paper describes these metal honeycombs for small motorcycles (Fig. 2), which were used on models intended to meet the 2005 Indian emission regulations, and the methods used to develop them.

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Fig. 1 Metal honeycomb substrates



Fig. 2 Outline view of muffler with metal-honeycomb catalyst on small sized two-wheeled vehicle for India model

2. Background of Development

A metal honeycomb substrate (hereinafter called a “metal substrate”) is manufactured as follows: A ferrite-based stainless steel flat foil and a corrugated foil are put together and rolled up to form a honeycomb core. The honeycomb core is inserted into an outer jacket made of ferrite-based stainless steel. Figure 3 shows the flat foils and the corrugated foil used in the honeycomb core.

The flat foil, corrugated foil and outer jacket are bonded to each other by brazing, diffusion bonding, laser welding⁽²⁾⁻⁽⁴⁾, or some other method. Currently, the main method is brazing, using an Ni-based filler metal (shown in Fig. 4) that permits a high degree of bonding freedom.

Metal substrates have previously been used in small motorcycles in certain regions such as Thailand, but in most cases their specifications were developed at the beginning of the 1990s, which was the peak of the small 2-stroke engine era. Compared to a 4-stroke engine of the same displacement, the reciprocating parts of a 2-stroke engine, such as the piston and connecting rod, were heavy, so engine vibration was strong. Also, such 2-stroke engine motorcycles were generally inexpensive by design, so some of these machines did not even have a balancer shaft. For this reason, the vibration acceleration generated by the engine vibration was extremely high, so high mechanical durability was demanded. The metal substrate was designed to be durable enough to prevent the honeycomb core from dropping out due to fatigue resulting from the vibration forces G (hereinafter called “vibration G”) generated by a motorcycle, as shown in a and b of Fig. 5. The method used



Fig. 3 Flat foil and corrugated foil

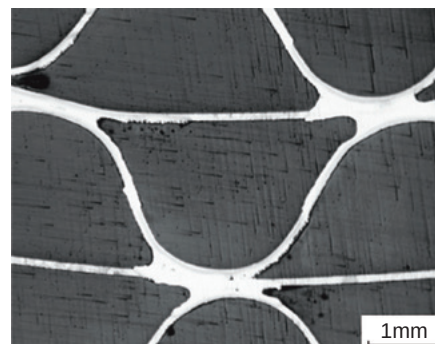


Fig. 4 Microstructure of cross section for Ni brazing

to obtain this durability involved increasing the bond area using Ni brazing filler metal to enhance the rigidity (Fig. 5-c).

However, the Ni brazing filler metal itself is expensive, so the question of how to minimize the amount of Ni brazing filler metal was of technical concern.

Recently, however, because of demands for clean exhaust gas, an increasing number of motorcycles are being fitted with 4-stroke engines⁽⁵⁾, which produce cleaner emissions than 2-stroke engines. Along with this, the required characteristics of the metal substrate have changed. The methods of mounting the engine and fixing the muffler are different from that of automobiles, so the required vibration G remains high, although the generated vibration G is about one half of that of a 2-stroke engine. The increase in the temperature of the exhaust gas due to the use of a 4-stroke engine causes a corresponding increase in the rate of temperature rise inside the honeycomb, which has brought about demands for higher hot-cold cycle durability. This situation is shown in Figs. 6 and 7 and also Table 1.

As mentioned above, the necessary characteristics for a metal substrate intended for a small motorcycle are as follows:

- Good vibration durability and hot-cold cycle durability
- Low cost

Knowledge about the brazing area and metal substrate properties determined from past developments are summarized in Table 2.

If the brazing area is taken as a parameter, it can be seen that the requirement of vibration durability is incompatible with the requirements of hot-cold cycle durability and cost. To satisfy all of these requirements, it is important to use the minimum amount of brazing filler metal necessary, and to use it as efficiently as possible. To enhance hot-cold cycle durability, it is important to minimize the thermal stress generated when the temperature of the metal substrate changes. The key to achieving this depends upon where inside the honeycomb, and also where between the honeycomb core and the outer jacket, brazing is carried out.

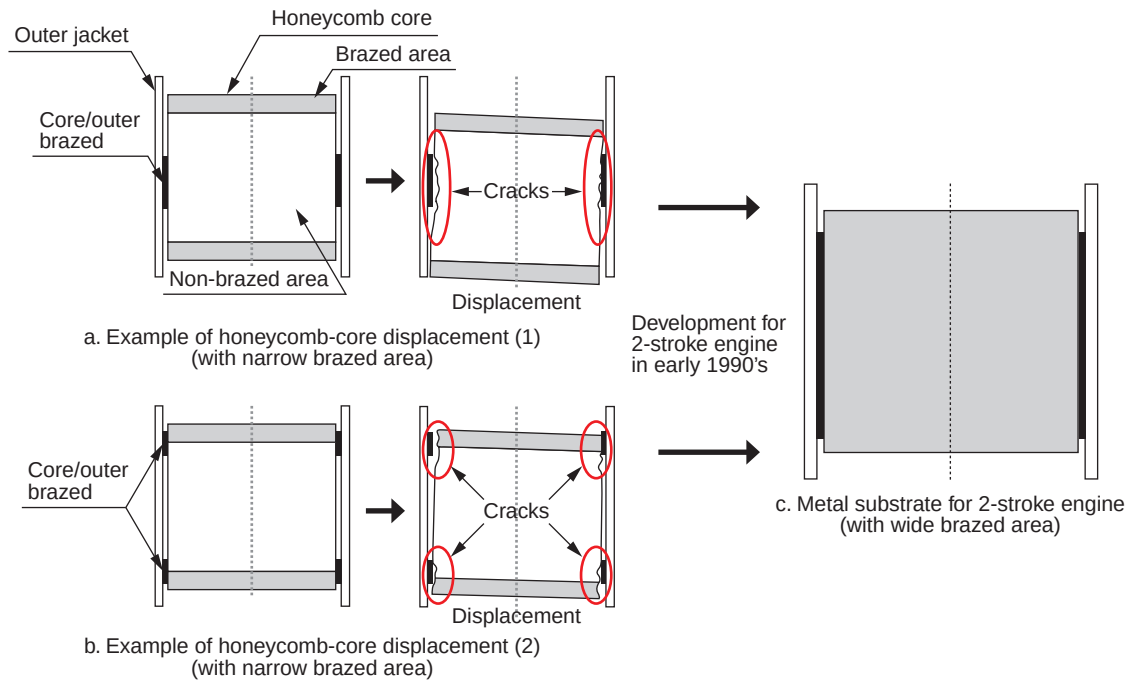


Fig. 5 Brazing joint structures of metal substrates

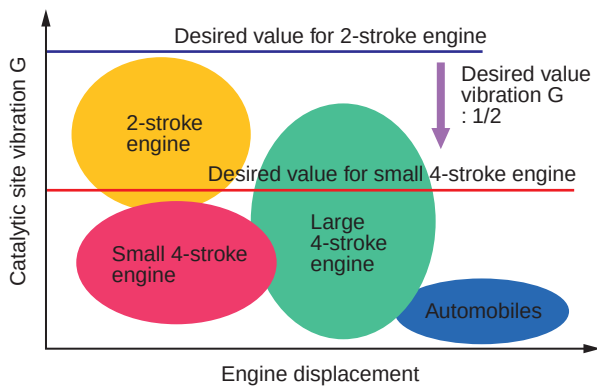


Fig. 6 Positioning of small size 4-stroke engine

Table 1 Comparison and demand characteristic of honeycomb catalyst load of 2-stroke engine and 4-stroke engine

Items	Comparison	Requirement characteristic
Highest temperature (See Fig. 7 area: A)	2-stroke >> 4-stroke	Vibration durability (High temperature fatigue strength)
Heating rate (See Fig. 7 area: B)	2-stroke << 4-stroke	Heat cycle durability

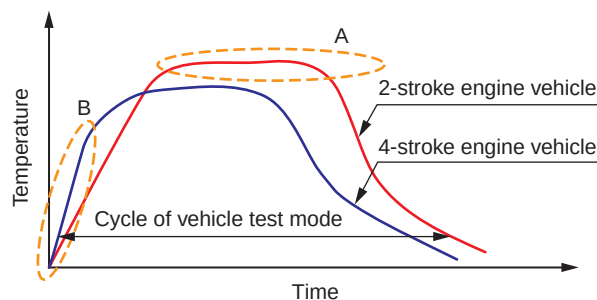


Fig. 7 Comparison of catalytic center temperature profiles during the endurance vehicle test mode

Table 2 Relationship between brazed area and properties of metal honeycomb substrates

Property	Brazing area Wide ↔ Narrow
Durability of vibration strength heat cycle resistant	Good ↔ Bad Bad ↔ Good
Cost	High ↔ Low

- Minimum brazing area necessary to enable the honeycomb to withstand the vibration G of a small motorcycle
- Optimization of the brazing locations to satisfy hot-cold cycle durability.

Also, to realize further cost reduction, it is necessary not only to reduce the amount of Ni brazing filler metal, but also to take into account productivity as well. To this end, a “simplified brazing design,” which obviates the need for a complicated production line, was adopted.

3. Contents of Development

3.1. Basic Concepts

The development concepts based on the model characteristics of small motorcycles are as follows:

3.2. Technical Methods of Specification Development

The technical methods used to satisfy the abovementioned concepts are as follows:

- Hot-cold cycle durability: Thermal stress CAE
- Vibration durability and hot-cold cycle durability: Unit durability test for new development

Hot-cold cycle durability of the metal substrate refers to the thermal fatigue life of the honeycomb core. CAE evaluation has recently been used to evaluate the thermal fatigue properties of exhaust system parts, particularly related to the thinner walls^{(6), (7)} of the exhaust manifold of an automobile. However, there are very few examples of a CAE evaluation being applied to a metal substrate. Also, because the phenomenon of thermal fatigue occurs in the plastic region, the few examples where CAE has been applied involved the implementation of Marc. or non-linear structure analysis⁽⁸⁾ computation which requires several days to complete. This method cannot be considered adequate from a practical viewpoint. In developing the new honeycomb substrate, general linear structural analysis was used, and a method of analysis in which the models, boundary conditions, and so on were optimized and used with thermal stress taken as an evaluation parameter. Figure 8 shows an actual example of heat transfer analysis using the model employed in this development.

Normally, when fatigue life assessment in the plastic region is carried out, it is not feasible to use stress as an evaluation parameter. However, a honeycomb metal substrate with conventional specifications has a durability level such that the core would not drop out, so there was no need to perform an absolute life assessment in this development project. Because the aim was to optimize the brazing locations to reduce thermal stress further, it was judged that thermal stress could be used as a relative evaluation parameter. As a result, it was possible to carry out screening in only a few hours, in contrast to the conventional evaluations in which prototypes with different specifications were actually made, and durability verification tests were carried out on an actual vehicle.

Concerning vibration durability, an apparatus was fabricated for a unit durability test in which vibration was applied while heating and cooling gases were alternatively pumped across the honeycomb substrate (this test is hereinafter called a hot-cold cycle vibration durability test), establishing a hot-cold cycle vibration durability mode that was correlated to an actual vehicle. Figure 9 shows an outline of this test apparatus. In this way, the appropriateness of the computed specifications from the viewpoints of vibration durability and hot-cold cycle durability were evaluated.

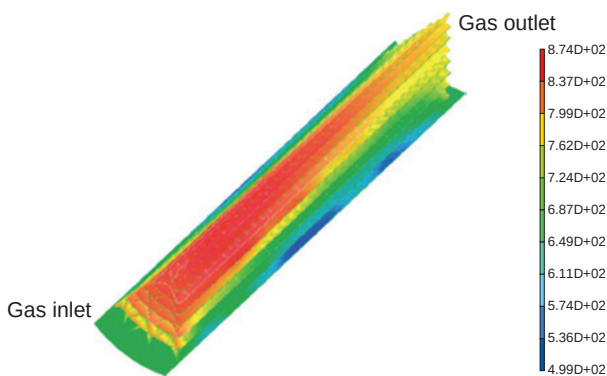


Fig. 8 CAE model; result of heat transfer analysis

3.3. Configuration of the Metal Substrate

As mentioned above, the component elements of a metal substrate can be classified into a honeycomb, an outer jacket and the brazing filler metal that joins them together.

For the honeycomb material, 20Cr-5Al ferrite-based stainless steel foil of 100 μm thickness was used because of its oxidation resistance and strength. Also, for the material of the outer jacket, Mo-added 17Cr-based stainless steel sheet (equivalent to JIS SUS436L) of 1.0 mm thickness was used because of its oxidation resistance.

Material that was equivalent to JIS BNi-5 was selected as the brazing filler metal. These materials are shown in Table 3.

3.4. Setting the Minimum Brazing Area

As shown in Fig. 10, the fracture load was measured for different brazing areas. Random variations of load and also the failure form were taken into account, and the brazing area that satisfied the specified load value was selected. This set value was no more than half of that used in the conventional 2-stroke engine specifications.

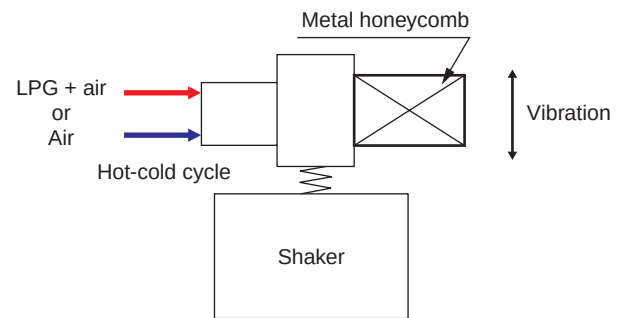


Fig. 9 Facility image of unit durability tests

Table 3 Composition of metal honeycomb substrate

Items	Materials
Honeycomb material	20Cr-5Al-REM (YUS205M1)
Outer jacket material	17Cr-Mo-LC (JIS SUS436L)
Brazing metal	Ni brazing filler metal (JIS BNi-5)

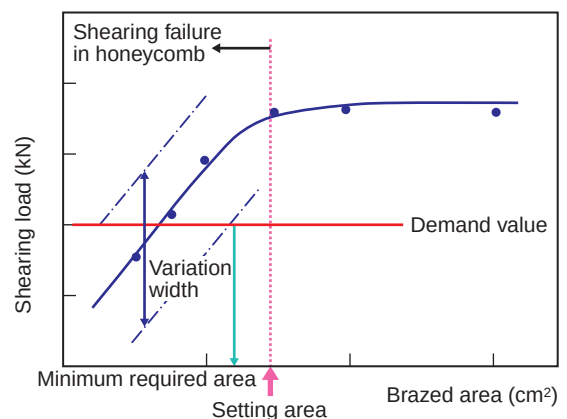


Fig. 10 Optimization of brazing area

3.5. Optimization of Brazing Positions

A small motorcycle was used, and the exhaust gas temperature and detailed temperature distribution inside the metal substrate were measured. The resulting values were assigned to the CAE model, and a CAE analysis was performed in the sequence of heat transfer analysis and thermal stress analysis.

The following three schemes were studied using as a standard the necessary bonding area obtained from the conventional metal substrate for a 2-stroke engine and the shearing load value.

Scheme A: Honeycomb core, and between the honeycomb core and the outer jacket (both brazed at the exhaust gas inlet side)

Scheme B: Honeycomb core, and between the honeycomb core and the outer jacket (both brazed at the exhaust gas outlet side)

Scheme C: Honeycomb core (brazed at the exhaust gas inlet side), and between the honeycomb core and the outer jacket (brazed at the exhaust gas outlet side)

From the CAE analysis results, scheme B, which generates the lowest thermal stress, was selected. Figure 11 shows an example of the actual analysis.

It was confirmed that by using the brazing specifications of Scheme B, the stress value at the outermost periphery of the honeycomb core, which is the weakest part of the metal substrate, was no more than about one half that of the stress value under conventional specifications (Fig. 12).

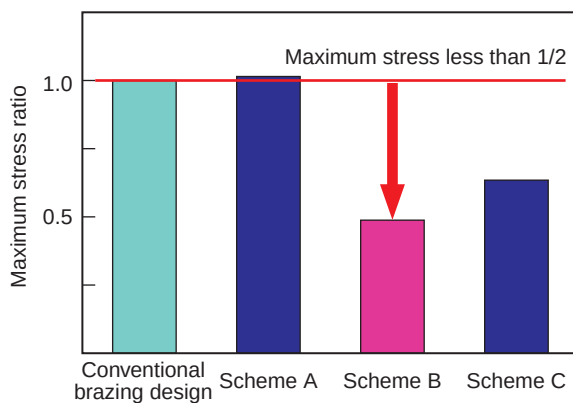


Fig. 12 Comparison of CAE results

3.6. Hot-cold Cycle Vibration Durability Unit Test Results

Based on the brazing position determined by CAE, the brazing width, amount of brazing material used, and other factors were optimized, and a test metal honeycomb was made. Table 4 shows the specifications of the test metal honeycomb.

A hot-cold cycle vibration durability test was carried out using this metal substrate, and the vibration durability and hot-cold cycle durability were evaluated. Figure 13 shows the external appearance of the metal substrate after the durability test. It can be seen that the core has neither dropped out nor been damaged due to the vibration G, and also that the cells in the vicinity of the outermost periphery of the core are neither deformed nor cracked, thus indicating conformity with the design scheme.

The test metal honeycomb was compared with the conventional honeycomb, and it was confirmed that the static shearing load after the durability test was about 2.5 times higher, as shown in Fig. 14.

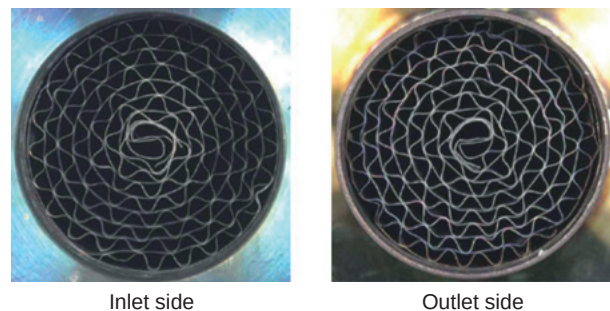


Fig. 13 Photograph of after unit durability test

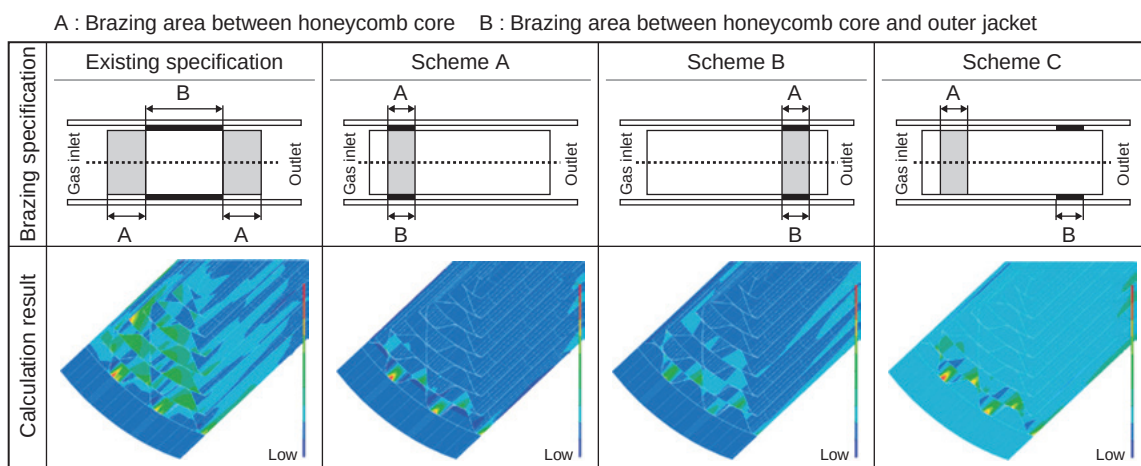


Fig. 11 CAE results of thermal stress analysis

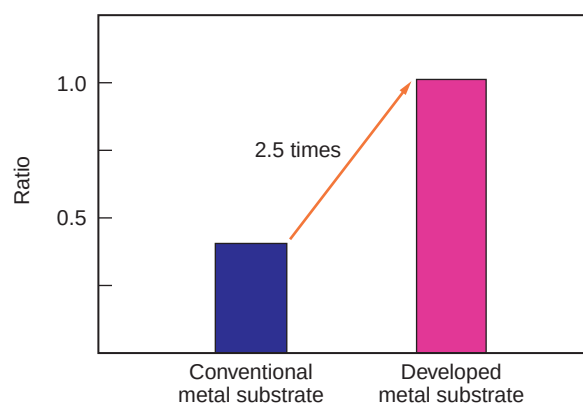


Fig. 14 Comparison of shearing load after unit durability tests

3.7. Evaluation of Durability in an Actual Vehicle

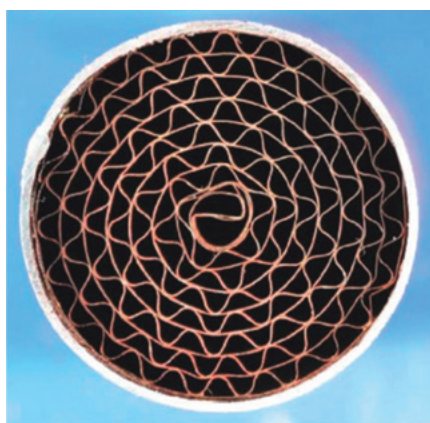
To make an overall evaluation of the function of the metal substrate as a component, the metal substrate indicated in Table 4 was coated with a catalyst, and subjected to a test in an actual vehicle.

(1) Mechanical durability

For the test vehicle, a model that generated a maximum vibration G roughly equal to the required vibration G was selected. After a durability test was performed with the metal substrate installed in a running vehicle, it was found that, just as in the unit test, the cells in the vicinity of the outermost periphery of the core were neither deformed nor cracked, thus indicating that the substrate had adequate durability (Fig. 15).

Table 4 Specifications of test metal honeycomb

Items	Specifications
Cell density	100 cpsi
Honeycomb core diameter	40 mm
Honeycomb core length	90 mm



Inlet side

Fig. 15 Photograph of after vehicle durability test

(2) Exhaust gas purification performance

To evaluate the deterioration of the exhaust gas purification performance, which includes the adhesion of the catalyst coating, the mounting construction of the exhaust pipe on which the metal honeycomb catalyst in the test vehicle was installed was derived, and an acceleration test using an actual machine was performed on the bench under conditions such that a vibration G of about twice that of the required vibration G was generated. It was confirmed that good adhesion of the catalyst coating layer still remained after the acceleration test. Also, as shown in Fig. 16, the substrate had exhaust gas purification performance at least equal to that of a conventional substrate.

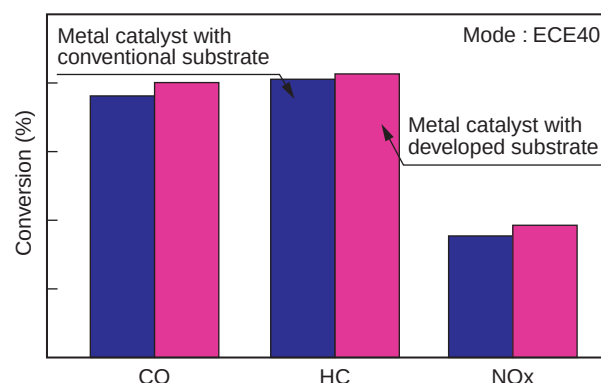


Fig. 16 Comparison of CO/HC/NOx conversion after vehicle durability tests

4. Conclusion

In the development of the metal substrate, methods of evaluating the thermal stress by CAE and hot-cold cycle vibration durability unit test were established. By using these methods, an inexpensive metal substrate that had both high vibration and hot-cold durability was developed.

- (1) The shearing load that would enable the substrate to withstand the vibration G produced by a small 4-stroke engine was set, and the necessary brazing area was determined. Compared to a conventional substrate, it was possible to reduce the brazing area to one half or less. In other words, it was possible to reduce the cost of the brazing material to one half or less.
- (2) To increase hot-cold cycle durability, a newly determined CAE method for estimating thermal stress in the honeycomb core was devised, aimed at optimizing the brazing position.
- (3) As a result of the newly established hot-cold cycle vibration unit test, vibration and hot-cold durability were evaluated, and it was confirmed that the static shearing load after the durability test was 2.5 times higher than that of a conventional substrate.

The developed metal honeycomb substrate for use in small motorcycles was first put into application in 2005 models destined for India. They are scheduled to be installed in future small motorcycles destined mainly for developing countries. Also, the evaluation method devised while developing the metal honeycomb substrate is scheduled to be used as an effective evaluation method in the diversification of specifications of metal honeycomb substrates, which would be expected from now on to achieve additional exhaust gas purification performance.

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References

- (1) Akamatsu, S., Ueda, M., Hayashi, T., Ouchi, K.: Development of Integrated Fuel Injection System for Small Sized Motorcycles, Honda R&D Technical Review, Vol. 17, No. 2, p. 1-7
- (2) Takada, T., Tanaka, T.: Development of a Highly Heat-Resistant Metal Supported Catalyst, SAE Paper, No. 910615 (1991)
- (3) Shibata, K., Ouchi, K., Nishizawa, K., Watanabe, N.: Development of Thinnest Wall Catalyst Substrate, 2002 JSAE Annual Congress Proceedings 20025062, No. 52-02, p. 1-4
- (4) Okubo, K., Nakamori, M., Kubo, M., Kaneda, Y.: Development of Laser Welded Metal Honeycomb Support for Motorcycle, 1998 JSAE Annual Congress Proceedings 9839641, No. 102-98, p. 9-12
- (5) Sugioka, K., Sekiya, Y., Hayashi, H., Kasa, K., Nakajima, H., Toriyama, M.: Development of a Scooter with 4-Stroke Engine – GIORNO Crea, HONDA R&D Technical Review, Vol. 11, No. 2, p. 9-14
- (6) Ando, S., Nakatsuka, J., Umeda, H.: Analysis of Thermal Stress in Exhaust Manifold, 1994 JSAE Annual Congress Proceedings 934, p. 89-92
- (7) Nakata, M., Ishii, K., Enomoto, M., Konishi, Y., Takahashi, S.: Evaluation of Thermal Fatigue Life on the Exhaust Manifold by Analyzing Restraint Ratio, HONDA R&D Technical Review, Vol. 11, No. 2, p. 57-66
- (8) Konya, S., Kasuya, M., Okazaki, Y., Imai, A., Kikuchi, A.: Numerical Analysis of Thermal Stress Distribution in Metal Substrates for Catalytic Converters, SAE Paper, No. 2002-01-0060 (2002)

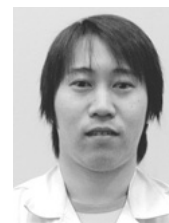
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