

The Development of Converter Canning Technology for Thin Wall Substrate

Shin'ichi TOSA*

Jun'ichi NAKADE*

Tatsuya OKAYAMA*

ABSTRACT

By applying a tourniquet type (rolling type) catalytic converter can, which is adaptable to the diameter of the substrate, a stable holding pressure can be successfully obtained. Additionally, by using of a double layer mat material, consisting of an inner layer of a high heat resistant alumina fiber and an outer layer of the current vermiculite containing material, the rate of holding pressure loss due to mat degradation is reduced. A combination of these two techniques allows the canning of a 1200 cell, thin wall substrate without breakage and, further, enables in-use durability requirements to be met.

1. Introduction

With increasing demands for reductions in regulated toxic substances in automobile exhaust for environmental reasons, improving the performance of exhaust cleaning catalysts is a critical area of development. One effective means of improving the performance of exhaust cleaning catalysts is the use of thin wall substrates with high cell densities, enhanced warm-up properties, and faster light-off⁽¹⁾⁽²⁾. However, thin walled substrates are difficult to can with conventional converter technology due to their reduced strength. A typical conventional canning method is to wrap the substrate in a mat material that combines alumina silica fiber and vermiculite and then compress the mat material with a clamshell type case so that the substrate is held by the surface pressure created by the compression of the mat.

One reason for the inapplicability of conventional canning technology to low-strength substrates is a structural problem with the clamshell case, which cannot assure stable surface pressure because of unequal pressure distribution and other factors. Additionally, the considerable decline in pressure due to fiber breakage and other forms of mat degradation necessitated high initial pressures to allow for subsequent degradation⁽³⁾.

In response, the authors both reevaluated converter cases from a structural standpoint and combined this with an improved mat material to develop converter canning technology for application to low-strength, thin-wall substrates. This paper describes said technology.

2. Breaking Strength of Thin Wall Substrates

Thinner walls generally mean reduced strength. Further, cells tend to deform during the extrusion molding of the substrate as a result of higher cell density. This deformation facilitates buckling and subsequently leads to reduced

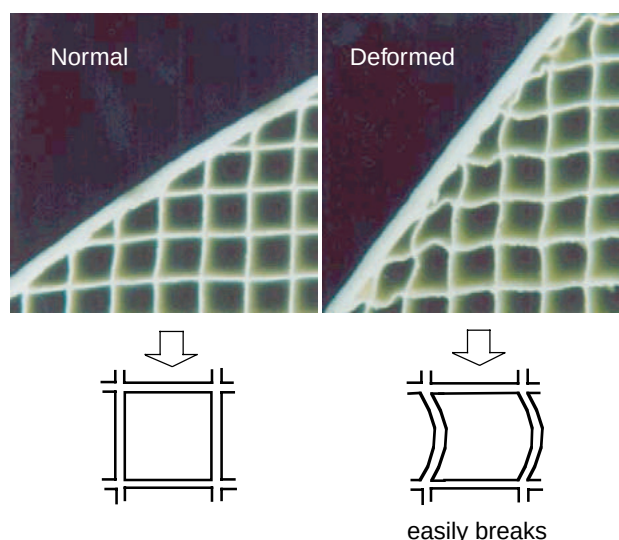


Fig.1 Cell shape of 1200 cell substrate

strength (Fig.1). Cell deformation is particularly likely to occur near the outer wall due to the unequal flow rate of the substrate material when it passes through the slit face plate. Isostatic strength, which is used to assess substrate strength is the pressure at which breakage occurs when the substrate's outer surface is subjected to water pressure or some other type of uniform pressure. Therefore, a cell's weak areas determines the cell's isostatic strength.

Isostatic strength according to wall thickness is shown in Fig.2. A 600-cell substrate has an isostatic strength of at least 20 kgf/cm² and can be canned at a surface pressure of up to 20 kgf/cm² without breaking. The lower isostatic strength of 900- and 1200-cell substrates limits them to a canning pressure of 5 kgf/cm² or less.

* Tochigi R&D Center

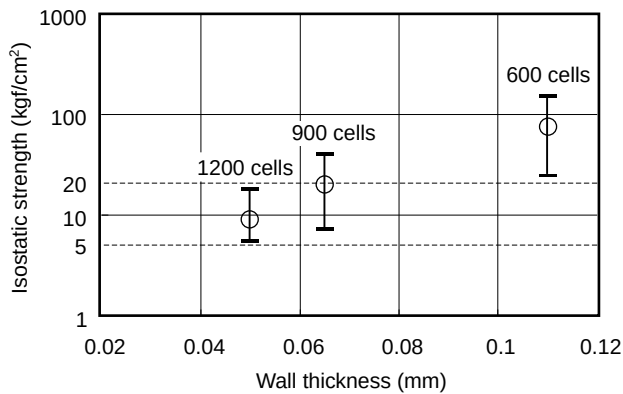


Fig.2 Actual isostatic strength of thin wall substrates

3. Technical Issues in Low Surface Pressure Canning

One method commonly used to hold a ceramic substrate in a stainless steel case consists of arranging a metallic mesh, mat or other holding material between the case and substrate, and utilizing the resultant pressure to hold the substrate in place.

A mat compressed and packed into a converter generates a surface pressure according to its packing density. When the surface pressure generated by the holding seal mat (the "holding pressure") exceeds the strength of the substrate, the substrate breaks. Further, as the substrate is subjected to forces such as vibration and exhaust gas pressure that try to move it ("moving force"), if the holding pressure is insufficient, the substrate will not be held stable. Therefore, surface pressure is the most important specification in converter design and it must always be kept less than the substrate strength yet higher than the minimum pressure needed to withstand moving force.

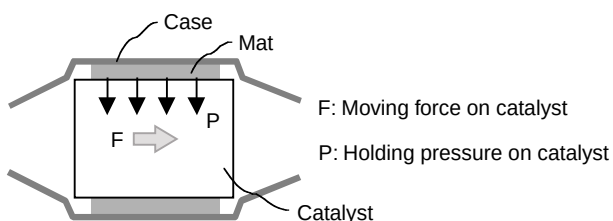
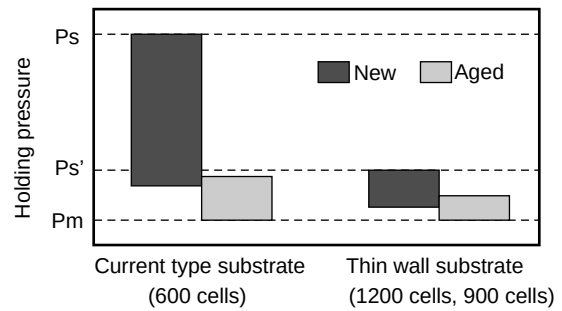


Fig.3 Converter schematic illustrating major design factors

Fig.4 expresses the relationship between substrate strength and holding pressure. The height of the bars in the graph indicate the surface pressure variation that results from uneven surface pressure distribution, dimensional variations in the substrate and case, and variations in mat weight. Maximum surface pressure, including this uneven surface pressure distribution and variations in components, must not exceed the upper limit for surface pressure, as determined by substrate strength. The right-hand bar in each bar pair represents the reduced surface pressure of the degraded holding material, and demonstrates the need for a minimum



Ps : Maximum pressure for minimum strength of 600 cell substrate
 Ps' : Maximum pressure for minimum strength of thin wall substrate
 Pm : Minimum pressure required to keep substrate in case

Fig.4 Required radial pressure range for a thin wall substrate

holding pressure, i.e., the holding pressure that must be maintained to resist moving force after degradation, and which must also allow for variation in components. As stated above, the holding pressure specification must be below substrate strength but high enough to resist moving force. This is a very narrow range for low-strength, high-cell-density, thin wall substrates, making canning difficult. These design guidelines entail three technical issues that must be resolved to achieve low surface pressure canning:

1. Uniform distribution of surface pressure
2. Adaptability to component variation and consistency of mat packing density
3. Minimization of surface pressure loss due to mat degradation

4. Improved Technology for Low Surface Pressure Canning

4.1. Assuring Uniform Distribution of Surface Pressure

Fig.5 is a schematic diagram of the clamshell type

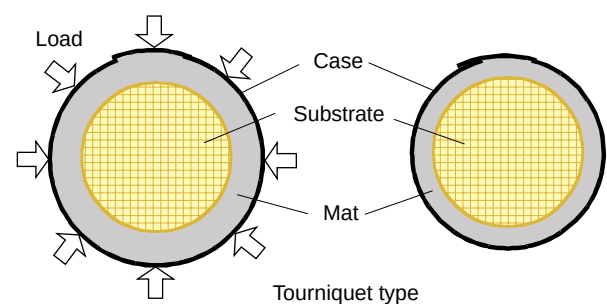
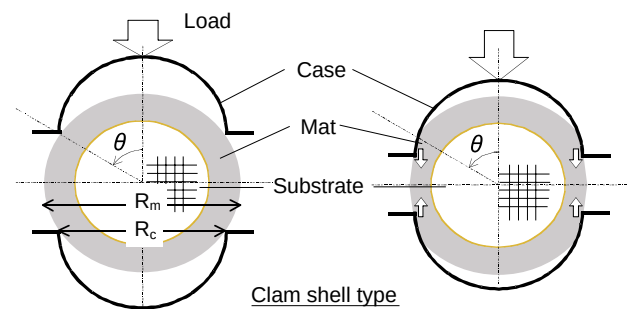


Fig.5 Schematic of canning technology

currently used in mass production and tourniquet type canning.

In clamshell type canning, a substrate is wrapped with a holding mat and canned through a pressurization process with a case having an upper and lower portion. The case outside diameter R_c is designed to be smaller than R_m , the outside diameter of the mat when it is wrapped around the substrate. The mat, once compressed and packed between the case and the substrate, generates a holding pressure. However, the portion of the case that first contacts the mat is the portion from the perpendicular to $\theta = \arcsin(R_c/R_m)$. This portion of the mat is dragged and compressed, by the case, as it moves perpendicularly. This results in variations in the mat's packing density and, consequentially, in an uneven distribution of surface pressure. This tendency toward uneven surface pressure distribution makes the clamshell technique unsuitable for low surface pressure canning.

The authors therefore examined the tourniquet type case as a construction that would assure uniform surface pressure distribution. This technique entails first creating the case by rolling a stainless steel sheet into a cylindrical shape and then inserting a substrate wrapped with a mat into this case, which is then compressed to complete the canning process. Unlike clamshell canning, this technique permits uniformity of surface pressure as the direction of holding seal mat compression during canning is aligned with the center of the honeycombs.

Fig.6 indicates the surface pressure distribution of clamshell and tourniquet type cases, and shows that the low angle area (i.e., $\theta = 30^\circ$) of a clamshell type case has a high pressure area that is generated due to variations in the mat. An area of high surface pressure also exists at the apex where $\theta = 90^\circ$. The higher surface pressure at the apex is most likely due to the substrate being compressed by the low-angle portion of the mat that is dragged by the case. In contrast, the tourniquet type case exhibits uniform surface pressure distribution.

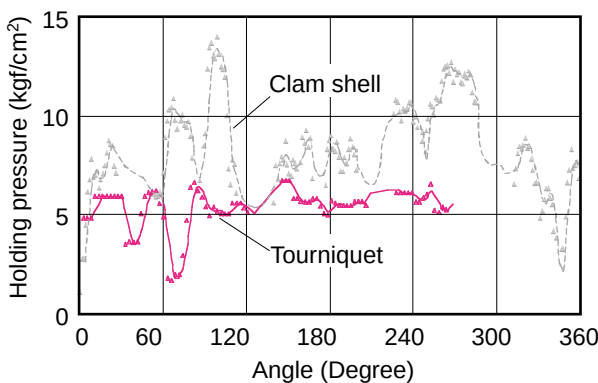


Fig.6 Comparison of clam shell and tourniquet canning techniques

In addition to the tourniquet type, the insertion type case construction also assures uniform surface pressure distribution. Insert type cases are constructed by first forming a cylindrical case of a predetermined diameter and then inserting the mat-wrapped substrate into the case while compressing the mat. Although a uniform distribution of

surface pressure is assured by the cylindrical case and the fact that the mat is compressed in the same direction as the substrate center, a rise in surface pressure occurs in the canning process as the mat must be sufficiently compressed to fit into the case during insertion.

Table 1 summarizes this comparison of case constructions. Based on these results, the tourniquet type case construction to achieve low surface pressure canning. Further, the tourniquet type construction facilitates variable control of case diameter as discussed in section 4.2.

Table 1 Comparison of each case structure to adapt lower level pressure

	Pressure distribution	Increased pressure while canning	Variable case diameter	Lower level pressure absorption
Clamshell type	Unevenly	Higher	Difficult	Impossible
Tourniquet type	Uniform	Lower	Easy	Possible
Insertion type	Uniform	Higher	Difficult	Impossible

4.2. Consistency of Mat Packing Density

Mat surface pressure is determined by packing density during compression. Variation in packing density can result from variations in substrate diameter, case diameter, and mat surface density and subsequently result in changes in surface pressure. Consistent surface pressure thus depends on the ability of the construction to adapt to variations in these components. To arrive at a method capable of efficiently achieving consistent surface pressure, the authors calculated the effect of each component on mat packing density, as determined with the following equation.

$$G.B.D. = \frac{W.A.}{CL} = \frac{2 \times W.A.}{D_{case} - D_{cat}}$$

G.B.D.: Mat packing density

W.A.: Mat surface pressure (weight per unit area)

CL: Clearance between the case and the substrate

D_{case} : Case inner diameter

D_{cat} : Substrate outer diameter

Three parameters were compared in terms of variability by calculating the change in packing density that occurred when one of the three parameters was changed within its range of variation (according to mass-production data for the component in question) while leaving the other two parameters constant. These results, in Fig.7, show how substrate diameter, which changes according to dimensions during extrusion molding and compression during baking, has five times the dimensional variability of the case. Therefore, as the substrate has the greatest impact on mat packing density, adaptability to this dimensional variation is effective.

The preceding shows tourniquet type canning to be a

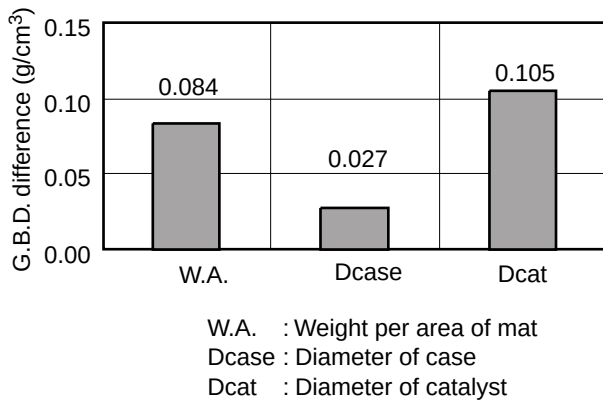


Fig.7 Effect of G.B.D. difference on each parts' variability

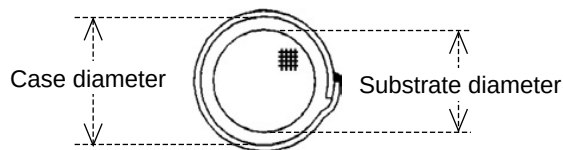
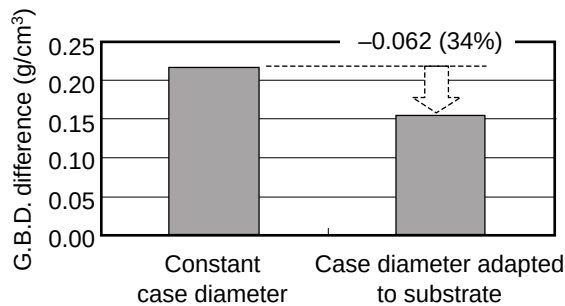


Fig.8 The effect of case diameter adapted to substrate

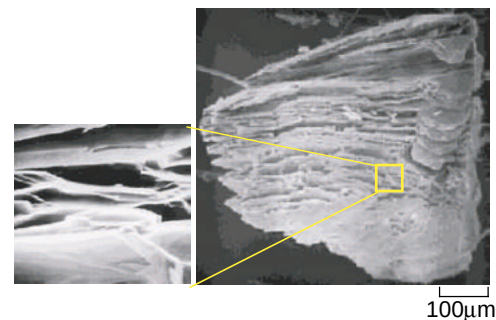
superior canning technique that makes it possible to measure individual substrate diameters and adjust case diameter accordingly. Moreover, this technique reduced variability in mat packing density by 0.062 g/cm³, and reduced mat packing density variation (i.e., surface pressure variation) by 34% beyond what would be possible with a constant case diameter (Fig.8).

Another possible method of tourniquet type canning, aside from controlling dimensions as described above is to wrap a belt around the case and pull with a constant load. Although the constant load is meant to assure uniform holding pressure by absorbing component variation, other variation factors such as case elasticity, friction between the belt and case, and load variations are generated rendering this technique unsuitable for the low surface pressure canning intended for application with a surface pressure of 5 kgf/cm² or less.

4.3. Minimizing Holding Seal Mat Degradation

Lastly, holding seal mat improvements designed to assure the requisite holding pressure after degradation are discussed. Current mass-production holding seal mats are comprised of an alumina silica ceramic fiber to which vermiculate has been added. Vermiculite is a natural mineral having a

multilayered structure of flat mica crystals containing for example metallic ions. Vermiculites possessing suitable high temperatures expansion properties are used in the mat (Fig.9). Vermiculite is added to the mat to prevent the drop in holding pressure that would otherwise occur at high temperatures due to increased clearance between the stainless steel case and the ceramic substrate, each of which undergo different rates of thermal expansion. Alumina silica ceramic fiber is a relatively inexpensive, amorphous ceramic fiber that has a 50% alumina content and which is commonly used as a heat insulator. Ceramic fibers such as this are created by hardening molten alumina silica into a fibrous form by means of compressed gas or centrifugal force, the result being a highly irregular structure, i.e., a vitreous state. A vitreous state is one in which a liquid has been supercooled to achieve a viscosity close to that of a solid without undergoing crystallization. As it is heated, a vitreous substance undergoes changes in state, first softening and then under going fluidization or crystallization. When the fibers such as those used in the mat material are subjected to a strong load at temperatures below 900°C, they start to soften. This leads to contraction that causes the fibers to break or deform. Above 900°C, precipitation of mullite crystals leads to extreme contraction, causing further breakage and deformation that is manifested as a marked functional degradation. Thus, mat improvement must begin with the



Chemical formula of vermiculite (example)

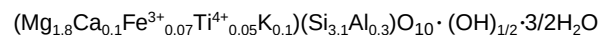


Fig.9 Microscope photograph of expanded vermiculite

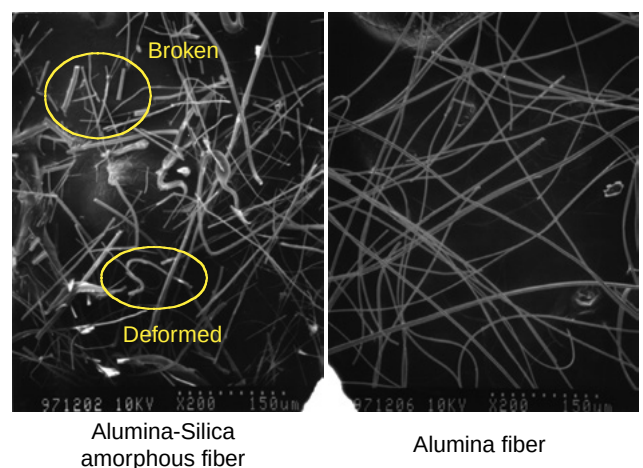


Fig.10 Fiber condition after bench durability test

selection of a fiber having superior thermal resistance. The authors therefore chose to investigate alumina fiber: a fiber that undergoes almost no contraction below 900°C, offers suitable elasticity, and has a high alumina content and a correspondingly low crystallization rate. SEM photographs of fiber conditions after bench durability testing (Fig.10) show that breakage and deformation of the alumina silica fiber occurred in the portions of the mat that had a temperature of 800°C. If extensive, this condition would cause the mat to lose its elasticity, reducing surface pressure to the point that the required holding force could not be obtained. The SEM photo of alumina fiber, however, reveals no such breakage or deformation, demonstrating that the material retains sufficient elasticity even at high temperatures.

Fig.11 shows the results of a comparative pressure retention performance test. In this test, mats were subjected to repeated heating and cooling and to changes in clearance comparable to that resulting from thermal expansion of a case. The residual pressure ratio was calculated from the load determined with a load cell. These results demonstrate the superior pressure retention performance of a mat made with alumina fiber. In addition, observation of the fiber after this bench durability test showed no difference between the pre- and post-test conditions, reflecting an improved thermal resistance.

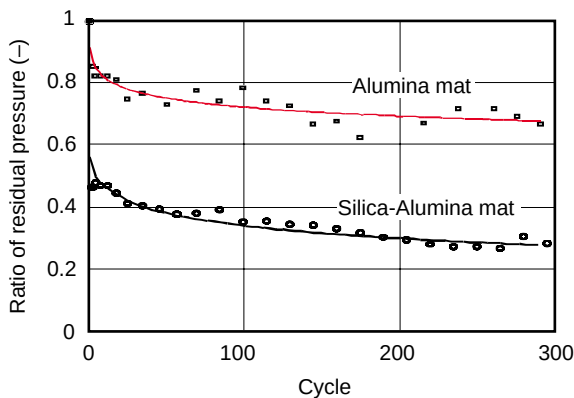


Fig.11 Durability test on thermal cyclic condition

The authors therefore decided to use this alumina fiber to create mats with improved pressure retention performance.

The results of a pressure test at different temperatures and different clearances (Fig.12) show that a mat made of alumina silica fiber containing vermiculite (the conventional mat) generated a maximum surface pressure at the high temperature after one cycle, whereas the alumina fiber mat exhibited maximum surface pressure at an early stage, that is, at a normal temperature. The residual pressure ratio after no more than 5 cycles was calculated relative to this maximum pressure ratio, which was assigned a value of 1 in both cases. The conventional mat underwent a large drop in pressure at the high temperature after two cycles, falling to a residual pressure ratio of 30% after five cycles. In contrast, the vermiculite-free alumina fiber mat underwent an expansion in high temperature clearance and exhibited a 30% residual pressure ratio at a high temperature. Thus, although

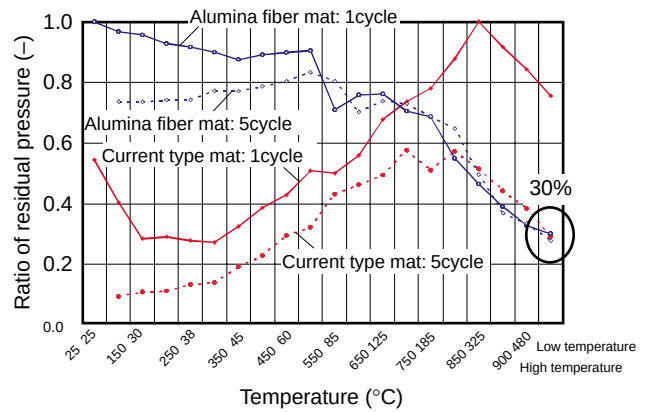


Fig.12 Pressure test on thermal cyclic condition

almost no pressure loss occurred that related to the cycles and ultimately, pressure retention performance was not improved.

To address thermal expansion of the case, the authors considered two-layer constructions such as that in Fig.13, in which a highly thermal resistant alumina fiber mat was placed on the substrate side, which is exposed to high temperatures, and a conventional mat was placed on the case side. The vermiculite in the conventional mat prevents pressure loss during thermal expansion of the case, while the alumina fiber minimizes degradation by acting as a heat insulator. Additionally, the elasticity of the alumina fiber mat provides holding pressure. Thus, this two-layer structure prevents pressure loss at high temperatures due to thermal expansion of the case while also minimizing pressure loss due to degradation.

Next, the authors sought to optimize vermiculite content and the weight per area ratios between the two layers.

Vermiculite, as already stated, is added to prevent pressure loss at high temperatures due to thermal expansion of the case, an appropriate amount must be added: adding too little fails to have the desired effect, while too much results in excessive expansion force. The authors placed a two-layer mat between upper and lower hot plates of different temperatures to determine the relationship of hot plate

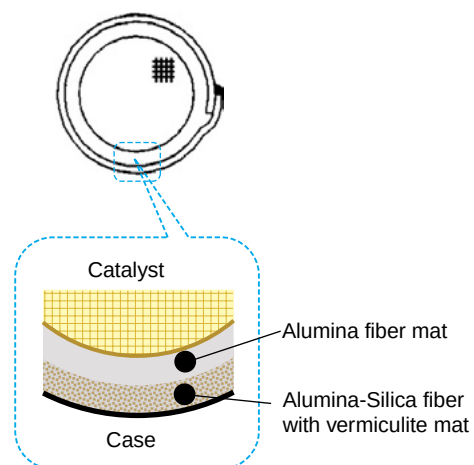


Fig.13 Illustration of double layer mat

temperature to changes in the two-layer mat's pressure under conditions in which clearance increased according to hot plate temperature (Fig.14). Pressure declined gradually prior to vermiculite expansion, but began to increase when the average temperature between the upper and lower plates reached 350°C; maximum pressure was reached at roughly 600°C. Mats differing in vermiculite content were prepared to determine the difference between pressure at normal temperature and maximum pressure at roughly 600°C. This showed that a 10% to 15% vermiculite content in terms of the total weight per area of the two layers resulted in a maximum surface pressure (at high temperatures) comparable to surface pressure at initial room temperature (Fig.15).

Using the vermiculite content thus determined, the authors next investigated the weight per area ratio in the two-layer mat. This was done by preparing a two-layer mat comprising alumina fiber mats of differing weights per area, performing a cyclic test under temperature change and clearance change conditions similar to those in Fig.14, and then determining surface pressure after 600 cycles. The results (Fig.16) show that a ratio between the two layers of 4:6 (alumina fiber mat:conventional mat) yielded the best pressure retention performance. A higher weight per area ratio for the alumina fiber mat resulted in less per-cycle surface pressure loss at high temperatures, but beyond 40%, the effect was diminished. This is believed to be because of the lower contribution ratio of the heat insulator layer to the conventional mat layer. In contrast, a high weight per area

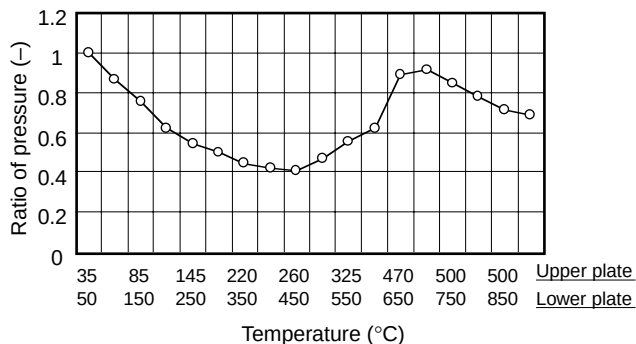


Fig.14 Pressure balance of room temperature and high temperature

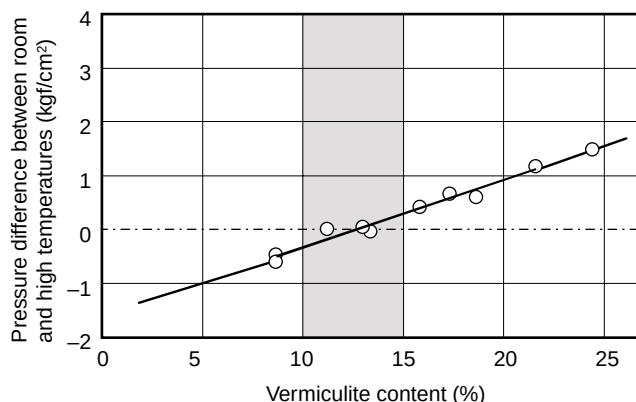


Fig.15 Best vermiculite content

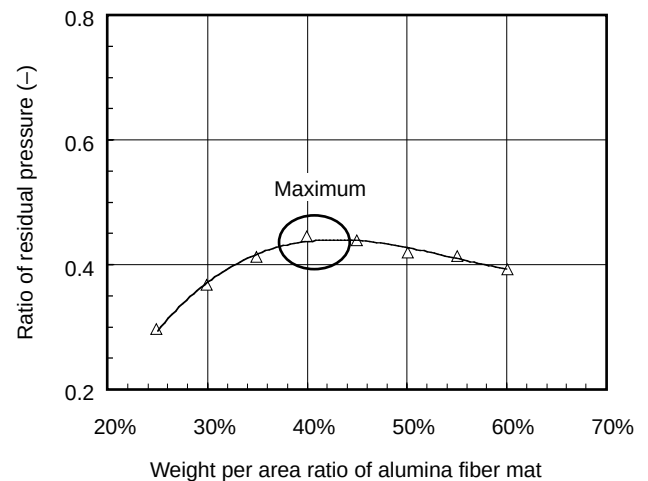


Fig.16 Pressure keeping performance according to the weight per area ratio of the alumina fiber mat

ratio for the alumina fiber mat tends to result in a slightly larger drop in surface pressure after maximum surface pressure at high temperature is reached in the first cycle. A mat's surface pressure normally undergoes a slight drop after reaching its maximum point; this is the mat's creep property. Particularly at high temperature in the first cycle, creep is large because the fiber binder inside the mat burns, freeing the fiber from its constraint, while the fiber itself moves due to thermal expansion, relocating itself so as to weaken the load. For this reason, alumina fiber will most likely undergo less breakage and deformation and have greater creep at a high temperature in the first cycle than the conventional mat. As a result, the per-cycle surface pressure retention performance at high temperature should offset the surface pressure drop due to creep at a high temperature in the first cycle, so that 40% is the highest surface pressure retention performance from initial room temperature through all 600 cycles.

To summarize the preceding, the optimum component ratio for the two-layer mat can be expressed with the following equation.

$$W.A.(total) = W.A.(a) + W.A.(c) \\ = W.A.(a) + W.A.(cf) + W.A.(cv)$$

$$W.A.(a)/W.A.(total) = 40\%(\pm 10\%)$$

$$W.A.(cv)/W.A.(total) = 10-15\%$$

W.A.(a): Alumina fiber mat weight per area

W.A.(c): Conventional mat weight per area

W.A.(cf): Weight per area of the conventional mat's fiber and binder

W.A.(cv): Weight per area of the conventional mat's vermiculite

W.A.(total): Weight per area of the overall two-layer mat

Finally, Fig.17 is a comparison of the surface pressure retention performance of a conventional mat and a two-layer mat with optimized components. This shows that in contrast to the conventional mat, whose surface pressure dropped to

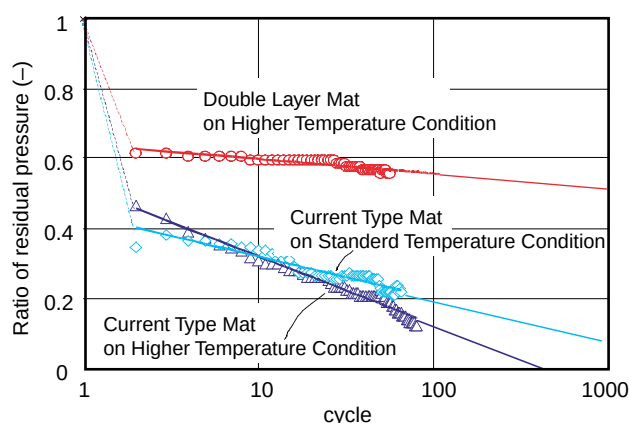


Fig.17 Pressure test under thermal cycle conditions

zero after 400 cycles, the two-layer mat retained roughly 50% of its surface pressure even after 1000 cycles.

5. Conclusion

In developing canning technology for thin wall substrates, the authors arrived at the following conclusions:

- The tourniquet type case structure is capable of achieving a uniform distribution of surface pressure and so is suited to low surface pressure canning.
- In a tourniquet type case, change in mat packing density was reduced 34% by adjusting case diameter to match substrate diameter.
- The drop in surface pressure due to degradation can be minimized with a two-layer mat having an alumina fiber mat on the catalyst side. Furthermore, optimizing the ratio between the two layers and the vermiculite content makes possible a 50% surface pressure retention rate after 1000 thermal cycles.
- Combining the above technologies permits canning at a surface pressure of 5 kgf/cm² or less, thereby allowing the use of low-strength, thin wall substrates, such as 1200-cell substrates.

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■ author ■



Shin'ichi TOSA



Jun'ichi NAKADE



Tatsuya OKAYAMA