Improvement of Noise Absorbing Thermal Conductance "Magnetic Induction Foaming" for In-Vehicle Use

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The automotive sector is currently undergoing a major transformation. This structural change is called "CASE" (connected, autonomous, shared, electric), and the electrification and digitization of vehicles are advancing rapidly. Under these circumstances, we have developed a magnetic induction foaming (MIF) technique for improving the thermal conductivity of sound absorbing polyurethane foam through magnetic field orientation, and succeeded in mass production of soundproofing products capable of achieving both thermal and noise countermeasures for in-vehicle electronics products. Recently, there has been an increasing need for heat dissipation and noise reduction for large products such as electric vehicle drive motors, in addition to in-vehicle small products. This time, focusing on the heat transfer structure of MIF, the heat dissipation property was improved by 2.5 times (up to 100 times of common urethane). Applying this method, this paper finds the possibility of MIF as a soundproofing cooling device that further enhances the air-cooling performance in addition to the soundproofing effect by covering the motor case.

Keywords: soundproofing, heat dissipation, polyurethane foam, EV, motor

1. Introduction

The automotive sector is currently facing a drastic transformation—on a level that only happens once in a hundred years. This structural change is being referred to as CASE—connected, autonomous, shared, and electric—with electric vehicles (EVs) and autonomous driving the central forces behind this change.

As the number of electronic components increases in the quest towards autonomous driving, demand for countermeasures against noise from the operation of such components is also rising, particularly in eco-friendly vehicles. This is because eco-friendly vehicles do not possess conventional engines, the noise from which usually masks component noise. As such eco-friendly vehicles become more widespread, the level of quietness required by users is also rising. This demand is even extending to electric powertrains,*1 such as in a drive motor.

Electric powertrains are expected to become progressively smaller in size and higher in output. Thus, the heat density in the powertrain will become higher and more efficient heat-dissipation technology will also be required.

Sumitomo Riko Company Limited has already developed a magnetic induction foaming (MIF)[(1)-(4)] technology, a new way of forming a sound-absorbent polyurethane foam possessing high thermal conductivity. Utilizing this technology, we successfully commercialized a soundproof cover, which delivers both heat dissipation and acoustic insulation, to be used for in-vehicle compact motors that suffer from Joule heating.

Based on this MIF foam's heat transfer structure, we then developed a technology that further improves thermal conductivity while reducing the weight of the foam. Moreover, we combined this technology with a metal plate with a view to actual commercial applications. This combined structural design created potential new value in this product as a soundproofing and cooling cover that offers both noise reduction and enhanced air cooling functions. This paper discusses the development process of the product.

2. Overview of the MIF Mechanism

When a magnetic particle is placed in a magnetic field, magnetic poles are created on the particle by magnetic induction. The magnetic body force, $\boldsymbol{F}^M$, born by the particle from the magnetic field can be expressed as follows:

$$\boldsymbol{F}^M = \boldsymbol{\mu} \cdot \nabla \boldsymbol{H} \qquad (1)$$

The magnetic particle in the magnetic field generates magnetic dipoles. Here the moment of the magnetic dipole is defined as $\boldsymbol{\mu}$. $\boldsymbol{H}$ is the magnetic field born by the particle. $\nabla \boldsymbol{H}$ here means the gradient of the magnetic field. This gradient comprises a macroscopic magnetic field gradient, which is generated by the magnetic field externally applied, and a microscopic magnetic field gradient, which is generated by the magnetic field induced by neighboring magnetic particles. The latter is known as magnetic dipole interaction.

In a "uniform field," where there is no magnetic field gradient, the magnetic particles are affected only by magnetic dipole interaction as there is no macroscopic magnetic field gradient. Thus, the particles form chain clusters in which particles are aligned and connected along magnetic lines.[(5), (6)]

Utilizing this physical phenomenon, we built heat bridges of magnetic particles inside polyurethane foam to dramatically increase the thermal conductivity in the vertical direction of the MIF structure.[(7), (8)]

Figure 1 shows a conceptual diagram of the MIF process. Within this reactive foaming process, viscosity increases more slowly than the speed of volume expansion. While this viscosity is still sufficiently low, we applied a uniform magnetic field to the foam to control the particles using the magnetic body force (Fig. 1 (D)). As resinification progresses, the magnetic particle structure is fixed creating a polyurethane foam with a unique internal structure (Fig. 1 (F)). Figure 2 shows two foams with and without magnetic field application. These photographs clearly show that magnetic particle heat bridges have been successfully created inside the polyurethane foam.

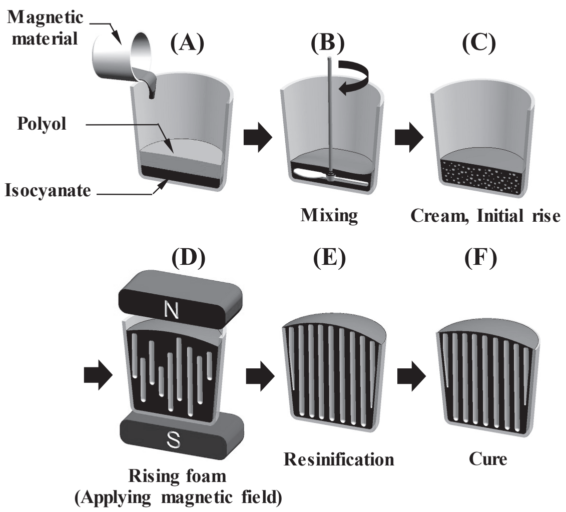


Fig. 1. MIF process

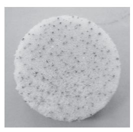
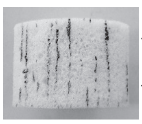
Sample / View	Not under magnetic field	MIF Under magnetic field
Top View		
Side View (Section)		 Magnetic Field

Fig. 2. Foams with and without magnetic field application

3. Thermal Conductivity Improvement in MIF Foam

3-1 Distribution of fillers and thermal conductivity

There is a method to increase the thermal conductivity of resins by increasing the percentage of particles (filler) that possess high thermal conductance. However, the thermal conductance of the resin significantly varies depending on how the filler is distributed within the resin (matrix)—even using fillers with the same thermal conductance.

The thermal conductance of the resin in which the filler is uniformly distributed can be determined as follows using the Bruggeman equation.

$$(1-\phi)=\frac{\lambda_c-\lambda_f}{\lambda_m-\lambda_f}\left(\frac{\lambda_m}{\lambda_f}\right)^{\frac{1}{3}} \quad \cdots\cdots (2)$$

Where, λ_c is the thermal conductance of the entire composite, λ_m is that of the matrix, and λ_f is the filler's thermal conductance.Φ is the volume fraction of fillers.

Our product's matrix is polyurethane foam and its thermal conductance is very low. Even uniformly distributing a filler with high thermal conductance does not create high conductance in the resulting composite. Figure 3 is an example of the calculated value of the thermal conductance for the volume fraction of the filler when λ_m = 0.03 W/mK and λ_f = 50 W/mK.

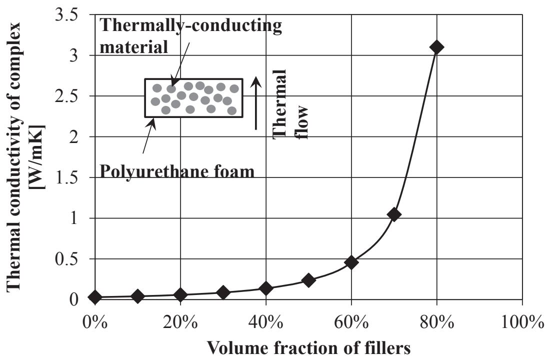


Fig. 3. Thermal conductance of a composite with uniformly distributed filler

The rise in the thermal conductance of the composite is negligible until the filler amount reaches 40 vol%, and the thermal conductance shows an exponential rise after the filler amount exceeds 60 vol%. This is because the filler particles do not establish contact with each other in the uniform distribution while the filler amount is low—in other words, thermal conductive pathways of filler networks are not established until the filler reaches a sufficiently large proportion.

To establish such thermal conductive pathways, Agari[9] suggested adding an alloy with a low melting point together with a thermal conductive filler. In his paper, Agari reported that the addition of a melted alloy with a low melting point helped form a continuous filler structure, resulting in significantly higher thermal conductance by the composite.

Using our MIF technology, it is possible to produce high thermal conductivity with a low filler content, which cannot be achieved with uniform filler distribution. This is realized through forming linear thermal pathways by aligning our exclusive magnetic particles (hereafter, main filler) along with the applied magnetic field.

Focusing on these thermal pathways, we have established a new method to add non-magnetic particles as a sub-filler (secondary filler) along with the magnetic main filler. With this method, the thermal pathways of the main filler formed by magnetic field orientation are bridged by the non-magnetic sub-filler, creating additional thermally conductive networks. This is expected to improve the thermal conductivity efficiency. Figure 4 shows a diagram of this concept.

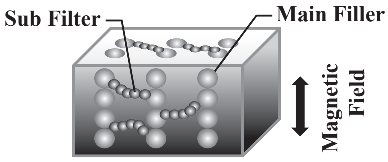


Fig. 4. Conceptual diagram of thermal transfer networks by fillers

3-2 Improving thermal conductance by thermal transfer networks

Utilizing the above method, we actually created a sample of the MIF urethane foam containing the main filler and sub-filler.

A section view of the sample created using X-ray CT imaging is shown in Fig. 5. The white parts shown in the figure are the fillers. As we expected, the sub-fillers bridge gaps in the main filler structure forming a network (hereafter, the developed material).

Figure 6 shows the thermal conductance values of the MIF polyurethane foams using conventional material and our developed material. The developed material improved the foam's thermal conductance up to a maximum of 3 W/mK. This value of thermal conductance is approximately 2.5 times greater than the maximum conductance of the foam using a conventional material, and almost 100 times greater than normal polyurethane foam.

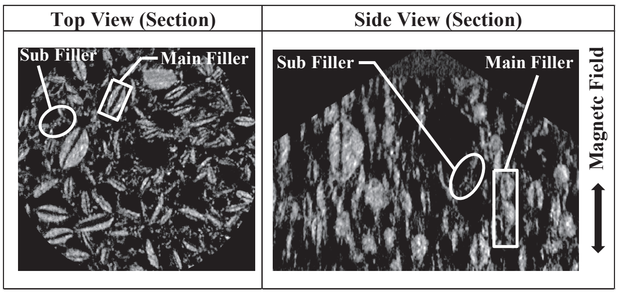


Fig. 5. Section view of the developed material by X-ray CT imaging

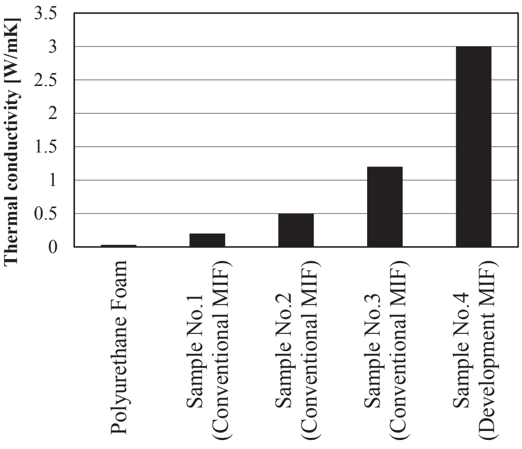


Fig. 6. Thermal conductance values of MIF foam samples (with conventional material and developed material)

4. Applications

4-1 Weight reduction and thermal conductance increase in MIF foam

The sample made in the aforementioned manner demonstrated that the increase in thermal conductance of the MIF foam is made possible by combining a main filler and a sub-filler. We then studied possible applications of the developed material.

As reported in a previous Technical Review,[7] MIF urethane foam possesses sound absorption characteristics derived from the porous structure of the foam, as well as sound insulation and thermal dissipation characteristics by orientating the additional filler. Thus, the foam is effective in reducing high-frequency noise from motors and other components.

When considering applying the MIF foam to electric powertrains and similar products, the MIF foam must possess more efficient thermal dissipation capabilities and lighter weight compared to conventional MIF foams because such large products generate a high calorific value due to their size.

To achieve more efficiency in thermal dissipation capability and weight reduction, we focused on one particular aspect of our developed material; that is, the non-magnetic sub-filler has a lower specific gravity than the magnetic main filler. Utilizing this characteristic, we reduced the amount of main filler to cut back the foam weight while also improving the thermal conductivity.

Figure 7 compares the features of the conventional material and the developed material. The conventional material used in this comparison was that with 0.5 W/mK, equivalent to Sample 2 in Fig. 6.

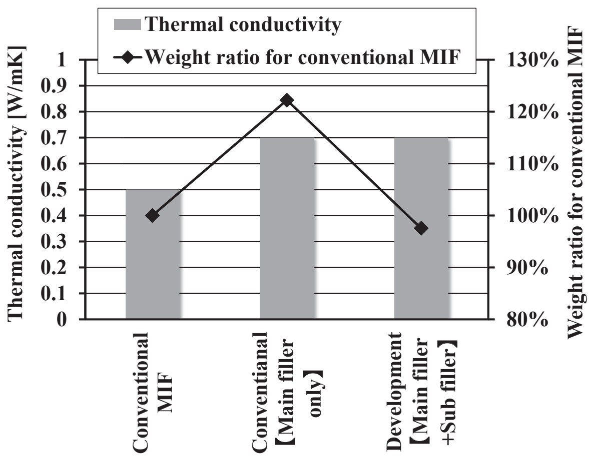


Fig. 7. Thermal conductance values of foams comprising different materials and weight comparisons

The weight of the developed material was 20% less than the thermal transfer material with equivalent thermal conductance made with the main filler only. It is 3% lighter than the conventional material that has a lower thermal conductance. At the same time, the developed material's thermal conductance was improved 1.4 times over the conventional material.

4-2 Heat dissipation performance test (Assessment of all-in-one structure comprising metal plate and foam)

Next, we conducted a heat plate simulation test in order to study the heat dissipation performance when used in an actual product. A schematic diagram of the test is shown in Fig. 8. We used an aluminum plate attached to a rubber heater as the heat source to simulate an aluminum motor casing.

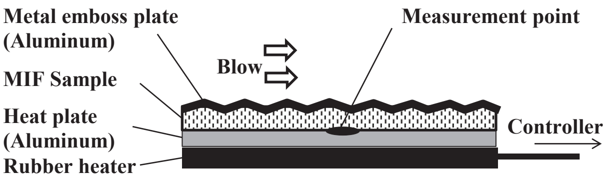


Fig. 8. Schematic diagram of heat plate test

Then, the sample was cooled by natural air cooling and forced air cooling. In the forced air cooling, an external fan blew air on the surface of the sample at a rate of 1.4 m/s.

We created a sample made of a sheet of the developed material, and recorded the temperature of the heat plate on its own and with the sample attached. Then, we studied the temperature of the plate after 3600 seconds (one hour) when the tested items reach a generally constant temperature. Further, we conducted the same test on another sample, in which the MIF foam directly grown on the outer surface of a metal plate (embossed aluminum sheet treated with black alumite) in order to gain even higher thermal conductivity. The size of both samples (one with the attached foam and the other with the directly grown foam) was 130 mm × 130 mm × t5 mm (the total thickness of the sample with directly grown foam was t5 mm). The heat plate was also the same size except in thickness.

Figures 9 and 10 show the test results. Compared to the test result of the heat plate only, the MIF foam alone provided a temperature reduction effect of ΔT = -15°C with natural air cooling. The embossed aluminum sheet with directly developed foam also provided a temperature reduction effect of ΔT = -17°C. We understood that the contribution factors of the temperature reduction were as follows. The heat transfer amount from the heat plate increased due to the lower heat resistance caused by the increased thermal conductivity of the MIF foam. In natural air cooling, heat is mainly released through thermal radiation.*2 Superior temperature reduction was achieved due to the higher thermal radiation ratio of the MIF foam and the black alumite treated surface of the embossed aluminum sheet compared with the aluminum plate.

In forced air cooling, the MIF foam alone showed a smaller temperature reduction effect of ΔT = -2.5°C compared

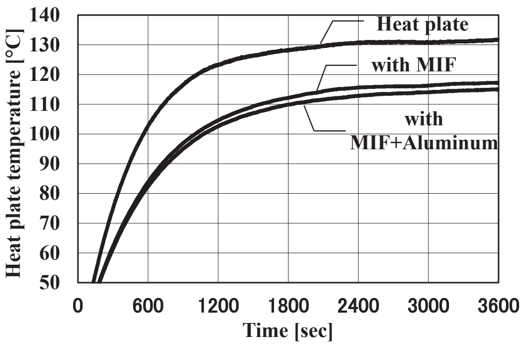


Fig. 9. Heat plate test results (Natural air cooling)

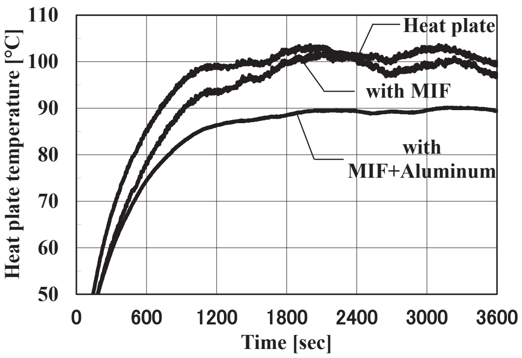


Fig. 10. Heat plate test results (Forced air cooling)

with natural air cooling, while the embossed aluminum sheet with directly grown foam provided ΔT = -10°C, a result similar to natural air cooling. In forced air cooling, convective heat transfer*3 largely contributes to the heat release, and thus the MIF foam is at a disadvantage in terms of heat release from its surface as it is covered with bubbles. However, combining the MIF foam with the embossed aluminum sheet increased the thermal conductivity of the surface as well as enlarging the heat release area, thereby increasing the heat-exchange efficiency with the air.

The above results demonstrated the potential of the MIF foam as a soundproofing and cooling device through combining the heatsink effect, which utilizes the external cover, and the increased heat releasing capability achieved by the filler network structure we had developed.

5. Conclusion

This development resulted in the following achievements:

(1) The MIF foam's thermal conductivity was increased through the thermal transfer network structure made by combining the main filler and the sub-filler.

(2) With a view to using the MIF foam for large products, such as an EV drive motor, a new MIF foam lighter in weight and higher in thermal conductivity was developed by focusing on the difference in specific gravity of the main filler and the sub-filler.

(3) Building the metal plate and the MIF foam as a single unit improved thermal conductivity to the outside of the cover. This enhanced the potential of our developed product as a soundproofing and cooling device that delivers increased cooling performance in addition to its soundproofing capability.

Moving towards the spread of EVs and autonomous driving, addressing operational noise and heat generation from various electronic components, including the electric powertrain, is inevitable. As components become increasingly smaller and higher in power output, they are also increasingly required to output less noise. The performance improvements of our MIF foam are expected to extend its application as a heat management product that proactively cools a component unit rather than simply suppressing the temperature increase.

• MIF is a trademark or registered trademark of Sumitomo Riko Company Limited, and covers the entire range of products, including soundproofing products, that utilize MIF technology.

Technical Terms

∗1 Powertrain: Refers to a mechanism that contains a motor or engine, and power transmitters, including a transmission and reducer, that deliver the motor power to the drive line. The mechanism is referred to as an electric powertrain in EVs and their main units are a motor, invertor, and reducer.

∗2 Thermal radiation: One type of thermal transfer phenomenon, in which heat is transferred as electromagnetic waves. The amount of heat transfer, Q, can be expressed as

$$Q = A \cdot \varepsilon \cdot \sigma \cdot \{(T_1 + 273.15)^4 - (T_2 + 273.15)^4\}$$

where Tn are the temperatures of each side of the material, with T_1 that of the higher temperature side and T_2 that of the lower temperature side. A is the heat-transfer area, ε is the emissivity, and σ is the Stefan-Boltzmann constant. The higher the emissivity ε, the higher the amount of heat transfer.

∗3 Convective heat transfer: Convective heat transfer refers to the phenomena in which heat is transferred through a fluid, such as air or cooling water. The amount of heat transfer, Q, can be expressed as

$$Q = A \cdot h \cdot (T_1 - T_2)$$

where h is the heat transfer coefficient, and the higher the h, the higher the amount of heat transfer. The heat transfer coefficient is variable depending on the type of fluid and how the fluid moves on the surface of the heat source, as well as on the shape and surface roughness of the material.

References

(1) Koji Tomiyama, Yasushi Ido, Patent No. 4906527 Sound absorbing material and structure (2007)

(2) Koji Tomiyama, Yasushi Ido "Development of Functional Materials by Using Magnetic Induction Foaming Method," Journal of Japan Society of Applied Electromagnetics and Mechanics, Vol. 16, No. 2 (2008), pp. 70-75

(3) Koji Tomiyama, Yasushi Ido, "Control of Foamable Resin Porous Structure by Using Non-uniform Magnetic Field," Journal of the Japanese Society for Experimental Mechanics, Vol. 8, No. 4 (2008), pp. 366-370

(4) Koji Tomiyama, Yasushi Ido, "Development of new In Mold Coating Method by applying Magnetic Induction Foaming Method," Journal of the Japan Society of Applied Electromagnetics and Mechanics, Vol. 18, No. 4 (2010), pp. 359-364

(5) G. L. Gulley and R. Tao "Structures of a magnetorheological fluid," International Journal of Modern Physics B, Vol. 15, No. 6-7 (2001), pp. 851-858

(6) "Functional fluids/Intellectual fluids," by Japan Society of Mechanical Engineers (JSME), Corona Publishing (2000)

(7) Koji Tomiyama, Shinji Yoshida, Naoki Katayama, Yasuo Suzuki, Yuji Kawai and Yasushi Ido, "Noise Absorbing Material with Thermal Conductance 'MIF'," SEI Technical Review, Vol. 79 (2014), pp. 51-56

(8) Koji Tomiyama, Shinji Yoshida, Naoki Katayama, Yasuo Suzuki, Yuji Kawai and Yasushi Ido "Heat Radiation Polyurethane Foam," Polyurethanes Magazine International, Vol. 13, No. 4 (2016), pp. 250-255

(9) Y. Agari "Development of highly thermal conductive polymer composites," Journal of Adhesion Society of Japan, Vol. 43, No. 8 (2007), pp. 325-330

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