Noise Absorbing Material with Thermal Conductance "*MIF*"

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With the advanced development of environment-friendly cars, such as electric and hybrid vehicles, automotive electronic products are required to have lower acoustic noise performance to create quiet vehicles. Polyurethane foam has high heat insulating property, therefore it is widely used as a sound proofing material; however, it cannot be used for electronic products like motors with Joule heat. This paper reports on Sumitomo Riko Co., Ltd.'s new polyurethane foaming method that significantly enhances the thermal conductivity. We also succeeded in the creation of sound proofing products that have high sound insulation property and thermal conductivity, by using this technology in combination with our original heat resistance polyurethane foam and molding technology.

Keywords: noise reduction, thermal conductance, magnetic induction foaming, polyurethane foam, motor

1. Introduction

With the advanced development of control / electrical components such as Drive Safety Support Systems or telematics services, more electronic products are required for use in automobiles, while the trend that appreciates low-fuel-consumption vehicles with clean energy requires quieter Electric Vehicle and Hybrid electric vehicle. Therefore, noise reduction for automotive electronic products, such as micromotors or inverters, are also required.

Sumitomo Riko Co., Ltd. has developed and mass produced unique polyurethane foam with high thermostability / flame retardancy as a sound proofing product to be used primarily for automotive products since 1997. Polyurethane foam is a porous material consisting of a foam part called a cell and skeletal part around which forms a polymer structure. It is used in a wide range of fields as light weight and flexible material for noise absorbing / sound insulation. However, it was not able to be used for electronic products which generate Joule heat when powered, due to its poor radiation performance of porous structure. **Figure 1** shows Scanning Electron Microscope (SEM) and a model image of a cross section of polyurethane foam.

The general method for improving the physical properties of polyurethane foam is chemical treatment, such as using a foam stabilizer to optimize the allocation design(1). Therefore, the properties, including thermal one, were only able to be changed in a limited area. As a countermeasure, we invented Magnetic Induction Foaming (MIF)*1 (2), (3) as a method of forming a new type of polyurethane foam which uses a magnetic field. This method enables changes of properties in fields not possible to change with chemical treatment. MIF has various possible applications, such as controlling mechanical physical properties by controlling cell structure(4) or improving noise absorbing property using with the In-Mold Coationg (IMC) method(5). Our intention, in developing this method, was to give radiation performance to polyurethane foam which is a heat insulation material. More specifically, we succeeded in forming a heat bridge by making magnetic heat conductive particles filled in a matrix formed by magnetic field orientation in an articulated structure to realize sound-proof polyurethane foam with higher radiation performance.

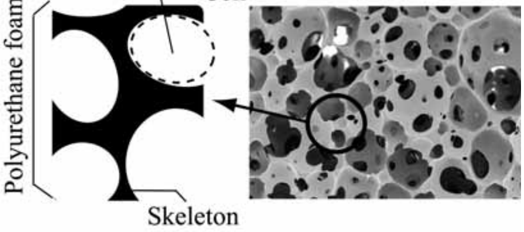

Fig. 1. SEM and model image of polyurethane foam porous structure

2. Mechanism of MIF

2-1 Behavior of magnetic particles in a magnetic field

When a magnetic particle is placed in a magnetic field, a magnetic pole is generated in the magnetic particle because of magnetic induction. The magnetovolume force $\boldsymbol{F}^M$ that the magnetic particle receives from the magnetic field is expressed as follow.

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

A magnetic particle in a magnetic field generates a magnetic dipole and defines the magnetic moment as $\boldsymbol{\mu}$. $\boldsymbol{H}$ is the magnetic field the particle receives. $\nabla \boldsymbol{H}$ means the magnetic field gradient. The magnetic field gradient consists of a macroscopic magnetic field gradient generated by the magnetic field which is applied externally and the microscopic magnetic field gradient generated in the inducted magnetic field by a peripheral magnetic particle. The later force is especially called a magnetic dipole interaction.

From the view point of magnetic field distribution, the condition of an applied magnetic field is largely divided into non-uniform magnetic fields and uniform magnetic fields. In a non-uniform magnetic field, magnetic material moves to an area close to the magnetic pole while forming cluster, and is distributed on one side, depending on macroscopic magnetic field gradient. On the other hand, in a uniform magnetic field, a magnetic particle receives only magnetic dipole interaction because a macroscopic magnetic field gradient does not exist, and forms "chain cluster structure" which connects along the line of magnetic force(6), (7).

We conducted a comparative verification of the calculation of such a phenomenon by doing a simple model experiment in visible particle diameter distribution. **Table 1** shows the primal experiment condition, and **Fig. 2** and **Fig. 3** show the regular condition of a magnetic particle in a uniform magnetic field and non-uniform magnetic field respectively.

Table 1. General condition for verification experiment

Experiment	Fig.2	Fig.3
Solvent	Water	
Magnetic flux density	Max 70 mT (Non-uniform)	70 mT (Uniform)
Particle	Sr-ferrite（size 100 μm～500 μm）	
Vessel	Polystyrene: cubic / inside edge 13 mm	
Dispersion ratio	1.0%: vol	
Simulation	Discrete particle method	

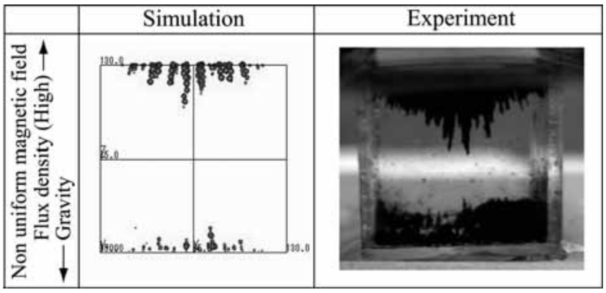

Fig. 2. Comparison of results from a simulation and experiment in a non-uniform magnetic field

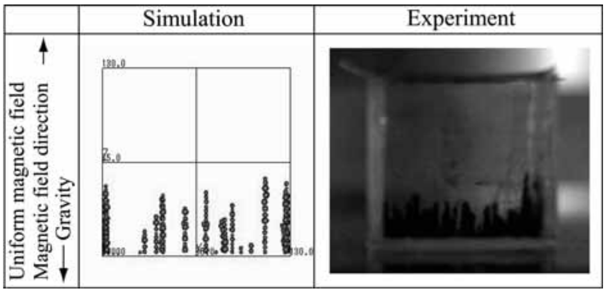

Fig. 3. Comparison of results from a simulation and experiment in a uniform magnetic field

For the calculation, we adopted a discrete particle method so the behavior of each particle could be detected. In addition to magnetovolume force and magnetic dipole interaction calculated in the **formula (1)**, we introduced counterforce generated by gravity and the contacting particles as an external force term to use as an original calculation model and source code*2 (8) in consideration of the unevenness of particles, which is qualitatively consistent with the results of the model experiment.

This results confirmed that the behavior of magnetic particles varies depending on the condition of the magnetic field, and that magnetic particles form a chain cluster structure along with a magnetic force line in a uniform magnetic field.

2-2 MIF forming mechanism

Before explaining the mechanism of MIF, the forming mechanism of polyurethane foam needs to be explained. However, its process is extremely dynamic chemically and physically, from the process of mixing raw materials to completing forming, while they overlap each other. We describe the foaming process of polyurethane foam, based on the general model of forming process presented by Turner, etc(9).

With polyurethane foam, the chemical reaction of two liquid source, polyisocyanate and polyol, generates polyurethane polymer at the same time that the reaction of polyisocyanate and water generates polymer with urea bond and carbon dioxide, by which the forming phenomenon proceeds. When the two fluids are mixed, the initial condition is liquid (**Fig. 4 (1), (2)**), and the generated carbon dioxide forms bubble nucleation while the mixture has a cream-like consistency, which initiates expanding (**Fig. 4 (3)**). At the same time that the reaction fluid continues to expand, its viscosity goes up due to a higher molecular weight (**Fig. 4 (4)**). In that way, the foaming phenomenon is completed by the balance of volume expansion due to gas evolution (and rising temperature) and the strength of the polymer foam film. When consecutive bubbles form, the foam film breaks at the end of the bubbling reaction and bubble gas blows off to be replaced with air (**Fig.4 (5)**). High molecular weight reaction continues after expansion is completed. This keeps the strength of the skeleton part increased for a while. We simulated the foaming condition in cup for explanation, but in actual molding, the material is poured into a mold for formation. The mold cavity is, consequently, transferred to the foam shape after formation.

For MIF, on the other hand, magnetic material is mixed as the third ingredient at the initial stage in order to give it physical control by the magnetic field (**Fig. 4 (A)**). At this point, the foam of the magnetic material can be either particle or suspension, in which the particles are deployed in the base fluid in advance, depending of the use. We used the foam of particles for this experiment. The behavior of the particles is determined by the magnetic field. However, as seen in the result of paragraph 2, a uniform magnetic field is required to be applied to obtain an even-structured formation. Although the conceptual diagram shows the case that a uniform magnetic field is applied, a non-uniform magnetic field can be applied for formation, if necessary.

One of the factors why such control is possible is that a certain period of time exists for a magnetic particle to

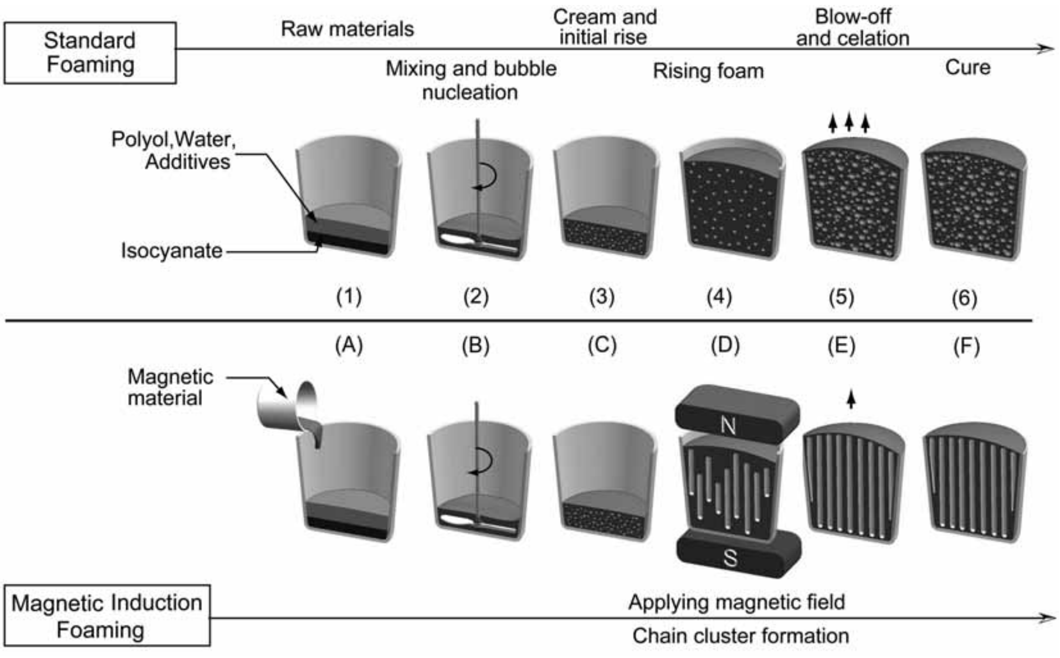

Fig. 4. Comparison of foaming process of regular polyurethane and MIF

move during bubbling because the expansion speed of viscosity is, basically, slower than the foam expansion speed. Therefore, application timing of a magnetic field is best in **Fig. 4 (C) - (E)**. Also, resinification of foam keeps the formation without destructing it and that brings the same result, even if a magnetic field is applied after the period.

3. Increase of Thermal Conductivity

3-1 Distribution of fillers and thermal conductivity

To increase the thermal conductivity of elastomer or resin, the known method is to highly fill particles (fillers) which have high thermal conductivity. However, thermal conductivity largely differs, depending on distribution of fillers, even when fillers with the same thermal conductivity are used.

As a simple model of MIF, we prepared Model-A which was a complex of thermally conducting material and resin in the parallel direction of thermal conduction. As a comparison model, we prepared Model-B which gave a simple distribution of thermally conducting material into resin in the foam of particles.

The thermal conductivity of the Model-A complex can be ideally calculated by rule of mixture.

$$\lambda_c = (1-\phi)\lambda_m + \phi\lambda_f \quad \cdots\cdots (2)$$

λ_c represents the thermal conductivity of complex, λ_m represents the thermal conductivity of resin (matrix), and λ_f represents the thermal conductivity of fillers. $\varnothing$ represents the volume fraction of fillers.

The Bruggeman formula is well known for thermal conductivity with a simple distribution of fillers, such as the Model-B complex.

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

In this invention, the matrix is polyurethane foam. It has very low thermal conductivity, and it is difficult to increase thermal conductivity significantly, even by simple distribution of fillers, which have high thermal conductivity. As an example, **Fig. 5** shows calculation values for the thermal conductivity of each complex, with the following values of assumption. λ_m = 0.03W / mK, λ_f = 50W / mK.

From these results, it seems to be difficult to increase thermal conductivity by a simple distribution of thermally conducting particles. On the other hand, Model-A results show that thermal conductivity can be increased, even with a low filling ratio, by orientating / connecting thermally

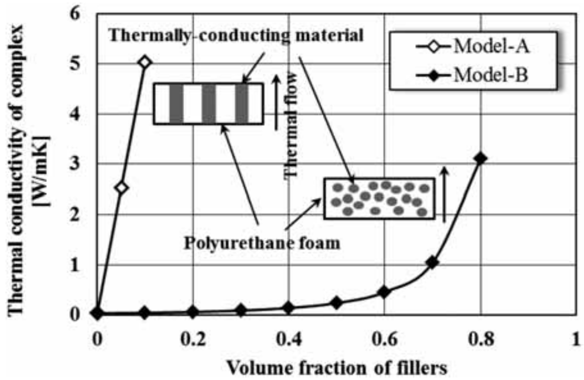

Fig. 5. Model calculation result of thermal conductivity

conducting particles in the direction of heat flow, which matches the concept of MIF.

3-2 Increasing thermal conductivity by MIF

Figure 6 shows the thermal conductivity of polyurethane foam formed by MIF. Regular thermal conductivity is 0.03 W/mK with polyurethane foam, while it can be a maximum of 1.2 W/mK with *MIF*, which makes thermal conductivity increased 40 times.

As fillers, we used our original complex magnetic particle. The volume fraction on the compounding design was range from around 0.1 percent to around 20 percent. We could not do a stringent comparison, because it is a model calculation, but it is clear that this increasing range is difficult to realize by simple distribution, as shown in the results of **Fig. 5**.

We observed the inner structure of an equivalent sample as No.3, and another sample of the same mixture not formed under a magnetic field by X-ray CT; **Fig. 7** shows the images. As a result, it can be said that, fillers are oriented / connected in *MIF* to realize high thermal conductivity as assumed.

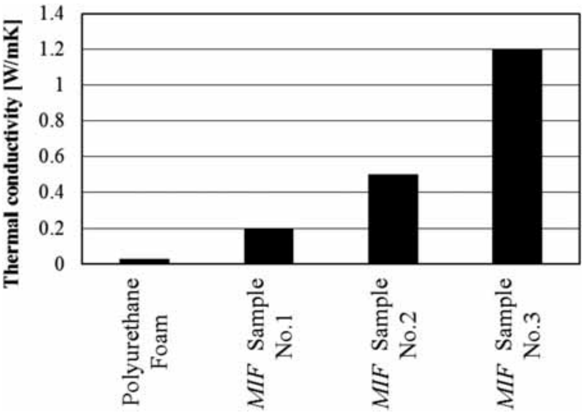

Fig. 6. Thermal conductivity of each sample (measured value)

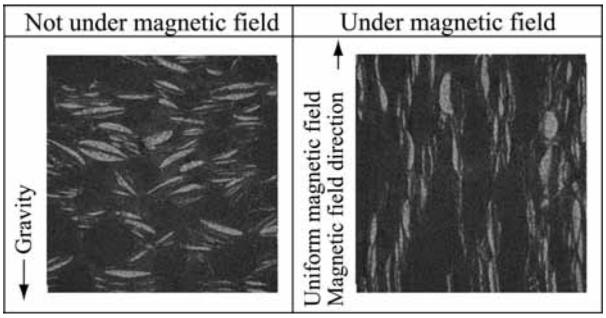

Fig. 7. X-ray CT image of each sample

4. Sound Performance of MIF

4-1 Characterictics of noise absorbing performance

Polyurethane foam has noise absorbing / sound proofing performance due to its porous structure and surface density, but the performance changes depending on the fillers and orientational structure.

Figure 8 shows a normal incident sound absorption coefficient of equivalent sample as No.1 (0.2 W/mk) at *MIF* sheet sample t20 mm. For comparison, a noise absorbing ratio of another sample with the same mixture not formed under a magnetic field and that of a base polyurethane foam, which did not use fillers, are shown.

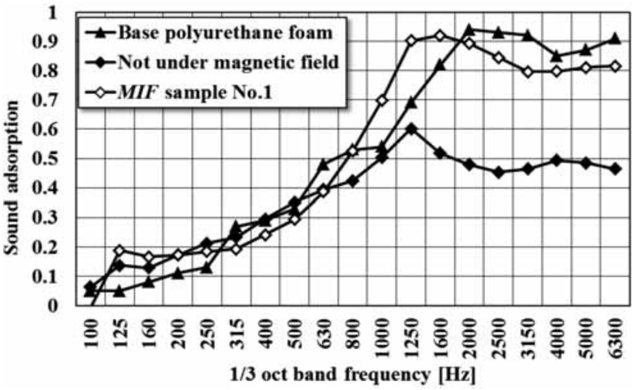

Fig. 8. Normal incident sound absorption coefficient of each sample

The results show sound absorption ratio gets worse at high frequency when fillers are simply distributed, compared with base polyurethane foam. A possible primal cause is the change of flow resistance (AFR), which is largely related with the sound absorption performance of the foam. Because of randomly filled fillers, the flow resistance against sound incident direction got higher. In *MIF*, on the other hand, fillers were parallel to the incident direction of the sound wave, which had less effect on the flow resistance. As a result, it realized a similar performance as base urethane in sound absorption ratio.

4-2 Characteristics of sound insulation performance

For sound insulation performance, it is generally known that surface density has a large impact based on mass law. However, the characteristics of the oriented structure of fillers are observed here. **Figure 9** shows measurement results of sound transmission loss with the equivalent sam-

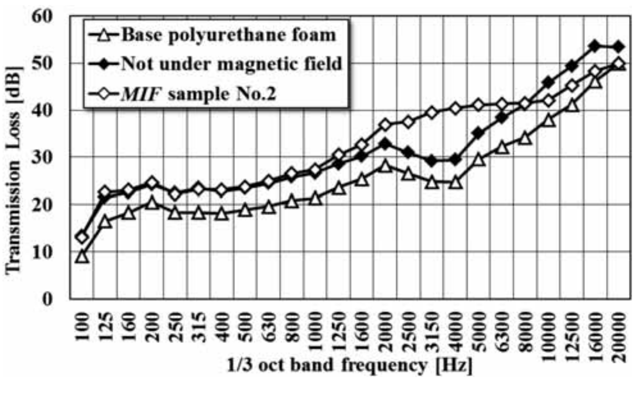

Fig. 9. Sound transmission loss of each sample

ple to MIF sample No.2 (0.5 W/mk) in the size of t6 mm × 300 mm square.

These results show sound insulation performance is increased simply by distributing fillers, due to higher surface density, compared to base polyurethane foam without filled fillers. In MIF on the other hand, compared to the sample to which fillers were simply distributed without applying a magnetic field, sound insulation performance increased by a maximum of 10 dB in the range of 1-8 kHz, although it had the same surface density. This could be because of a smaller impact of coincidence effect*3 in the band frequency after Young's modulus of the sample changed due to oriented structure of fillers. This sound insulation performance of MIF sample No.2 (0.5 W/mk) t6 mm is as high as that of t1 mm steel plate.

5. Verification of Effect by Motor Cover

To verify the effect with actual product, we performed an operation test using a compact all-purpose DC motor. The motor was a 16 V constant voltage drive with a simple shape of a cylinder around ø36 mm. For this motor, we formed MIF sample No.2 (0.5W/mk) equivalent material by molding to make a sound proof cover. **Photo 1** shows the appearance of the sound proof cover. The orientation was in the direction of a fin shape equipped above and under the cover. **Figure 10** shows the measurement results of the motor noise level in the position within 100 mm.

These results confirm the noise reduction effect, about 10 bB at overall value, against high frequency noise, which is peculiar to motor noise.

Photo 1. Sound proof cover

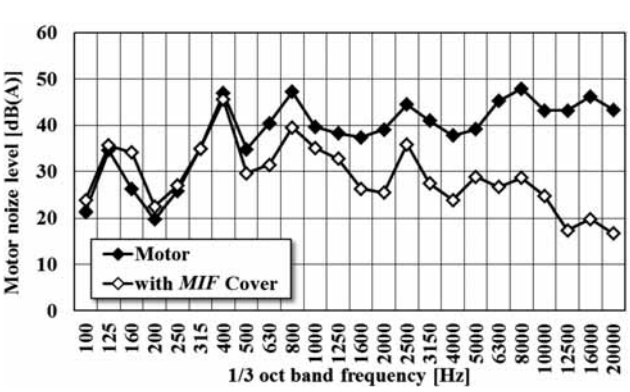

Fig. 10. Motor peripheral noise level

We also performed an experiment on measuring motor surface temperature to see the radiation effect of *MIF* against heat generation by joule heat of motor. **Figure 11** shows the measurement results.

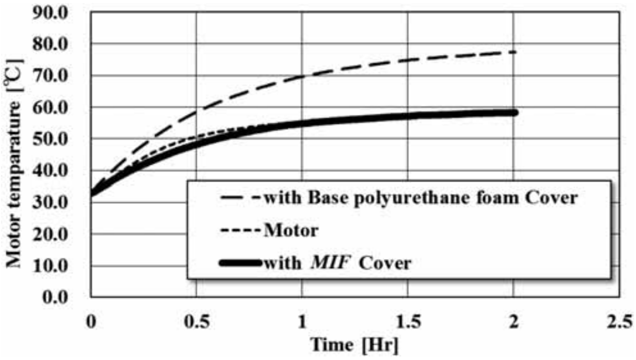

Fig. 11. Motor surface temperature

With the cover of regular polyurethane foam, the motor surface temperature went up around 20˚C higher than unit drive due to its heat insulation effect. The experiment with the cover using *MIF* recorded a similar curve of rising temperature as the unit simulated a two hour drive.

These results show it is possible to create a sound proof cover which serves both as radiation and sound proofing by combining *MIF* and molding.

6. Conclusion

We succeeded in largely increasing thermal conductivity of polyurethane foam by Magnetic Induction Foaming (MIF) to develop noise absorbing material which has radiation performance (*MIF*) for practical use. We also found some good characteristics of polyurethane foam in sound effects by MIF.

In the future, it is assumed that more electrical components will be equipped in many products, including automobiles, and noise reduction of electronics part will be in high demand. *MIF* is expected to be used in a wide range of ways as a material which can be a solution for heat and noise issues.

· *MIF* is a trademark or registered trademark of Sumitomo Riko Co., Ltd.

Technical Terms

∗1 Magnetic Induction Foaming (MIF): The new technology means sound proofing products using Magnetic Induction Foaming (MIF). In this report, we do not use the trademark on MIF as a technical name to distinguish it from the products.

∗2 Original calculation model and source code: Original source code was created by Ido lab at Nagoya Institute of Technology. Extended calculation model was created by the joint work of Sumitomo Riko Co., Ltd. and Ido lab.

∗3 Coincidence effect: When sound wave is incidental to sound insulation material, the coincidence of vending vibration of plate subjected to acoustic excitation, and wave length of sound wave components in oblique direction, causes a resonant state, which lowers sound insulation performance rapidly after specific frequency band. It is called coincidence critical frequency and it is determined by Young's modulus or the surface density of the sample.

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