Highly Conductive Porous Metal Materials Enhancing Cooling Device Performance

Toru MAEDA*, Atsuki MITANI, and Ryohei KOBAYASHI

In response to the tightening international environmental regulations such as carbon neutrality and CO_2 emission reduction, the importance of thermal management has been emphasized in electronic products and automotive electrified products, where heat generation density is increasing year by year. In addition to the cooling mechanisms such as air cooling and water cooling, which have been the mainstream so far, there is an anticipated expansion of cooling mechanisms with excellent heat dissipation capabilities, such as heat pumps, vapor chambers, and heat storage systems. The effectiveness of these systems largely depends on the capabilities of heat exchangers and heat storage devices. To enhance their performance, we have developed porous metal materials that have both high thermal conductivity, high porosity, and micropore size. These materials can contribute to the reduction of CO_2 emissions by reducing the energy required for cooling.

Keywords: porous metal, high thermal conductivity, heat exchange, heat storage, thermal management

1. Introduction

Recently, growing communication data volume and processing capacity for expanding virtual space and autonomous driving have been significantly increasing the heat generation density of communication, as well as the processing semiconductor devices and power devices that support their operation.(1) To address this issue, various kinds of cooling systems, such as air, water, and vapor cooling systems, are being used. While CO_2 emission regulations and carbon neutrality-oriented policies are being promoted worldwide, the use of electricity generated from sources other than fossil fuels is encouraged. However, such measures currently face limitations, and thermal management, including energy saving of cooling systems and reuse of recovered heat, is important.

In this thermal management, it is expected that innovation of constituent technologies, such as (1) heat exchange from a heat source to a refrigerant, (2) heat transfer, and (3) heat storage/thermoelectric conversion, will be required. From this perspective, we have developed a porous metal material featuring high thermal conductivity,*1 a high specific surface area, and high porosity through the powder metallurgy process.*2 This paper reports on the results of the new material development.

2. Application of Porous Metal Materials to Heat-Dissipating Devices

First, regarding heat exchange, the lower thermal resistance of heat transfer from a heat source to a refrigerant, the smaller temperature difference in a heat exchanger, which can be achieved by facilitating heat transfer through the thinner diameter and more complex shape of the flow path, and lower heat transfer pressure loss of the refrigerant are important from the perspective of efficient thermal conduction of a refrigerant.(2)

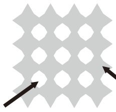
The characteristics of developed porous metal are shown in Table 1. For comparison, the characteristics of low-density sintered material produced by sintering without compression and plated material(3) are also shown. The developed material uses highly electrically conductive metal, such as pure aluminum or pure copper, as a structure, and features its closely packed structure and relatively high thermal conductivity in a high porosity area of 60% or more, which have been achieved by an improved method using our high-pressure forming technique used to manufacture sintered components based on the manufacturing method of porous metals(4) through the publicly known powder metallurgy process.

The first item of the required characteristics, the thermal resistance of heat transfer from a heat source to a refrigerant, is expected to be significantly reduced by using high thermal conductivity. In addition, integral forming with a closely packed structural body will seamlessly braze porous metal to the heat source of a dissipator, helping reduce thermal resistance. Photo 1 shows a prototype of seamlessly brazed products.

The second and third items of the required characteristics, the contact area with a refrigerant and the heat transfer pressure loss of a refrigerant, are determined by the balance of the specific surface area and the porosity of the porous metal, and generally have a correlation with the pore diameter. There is a tradeoff between them: a smaller diameter is desired by the former and a larger diameter by the latter. We have improved the powder metallurgy process for the developed material so that the specific surface area and the porosity can be independently controlled in order to minimize the tradeoff as far as possible. In view of the fourth item, or the addition of irregularities to a refrigerant, porous metal material, which has fluctuations in the diameter of the microeconomic flow path in a cycle of 1 mm or less, is expected to have an advantage.

Second, regarding heat transfer, we focused on loop heat pipes using wicks made of porous material, and no

Table 1. Characteristics of developed porous metal

Manufacturing process	Powder metallurgy process (developed)	Powder metallurgy process (conventional)	Plated process[3] (conventional)
Internal structure (conceptual)	 Open pore, Metal skeleton		
Pore size (μm)	5 - 1000	5 - 100	400 - 3000
Specific surface area (m^2/m^3)	$10^4 \sim 10^6$	$10^3 \sim 10^6$	$10^2 \sim 10^4$
Porosity (vol%)	60 ~ 85	40 ~ 70	50 ~ 98
Thermal conductivity* (W/mK)	20 ~ 50	~ 5	-
Electric conductivity* (S/m)	4.0×10^6	-	$\sim 1 \times 10^6$
Tensile strength* (MPa)	5 ~	-	~ 1
Apparent density* (g/cm^3)	0.6	-	-

* Typical values for porous material consists of pure-aluminum

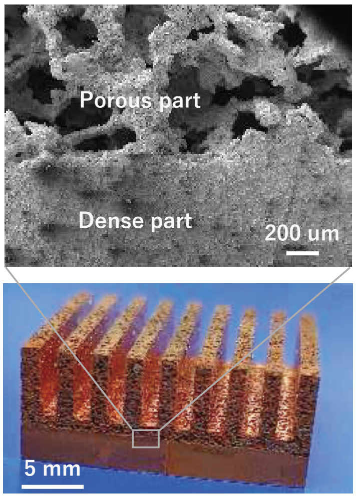


Photo 1. Seamlessly brazed prototype

electricity. Vapor-type loop heat pipes, which vaporize a refrigerant using energy from a heat source to obtain driving energy, and ferrofluid-type loop heat pipes, which use the magneto-volume effect of ferrofluid caused by the magnetic-non-magnetic transition to obtain driving energy, have been studied.[(5),(6)] Their performance will be improved by using porous metal for energy conversion.

Finally, regarding heat storage, the application of phase-change material (PCM), which operates in the specified temperature range, has been examined.[(7),(8)] However, PCM has several issues, such as large volume change, difficulty of shape retention, leakage when liquefied, and slow response speed due to the low thermal conductivity of PCM. By impregnating porous metal whose pore diameters are appropriately reduced with PCM, the confinement effect caused by the capillary tube force when liquefied will help produce heat storage material whose volume and shape does not change when liquefied, and the high thermal conductivity of the porous metal will help compensate for the low thermal conductivity of the PCM.

From these perspectives, porous metal produced through the powder metallurgy process is expected to be highly effective for heat exchangers, loop heat pipes, and heat storage material. The following chapter describes the results of their basic performance evaluation.

3. Basic Performance Evaluation of Heat-Dissipating Devices

3-1 Effects on heat exchangers with the porous metal material

To evaluate the basic performance of heat exchangers, we established the evaluation system shown in Fig. 1. We used porous metal made of pure copper (purity: 99.5%) with a porosity of 80 vol%. As for the structure between the upper surface of the housing specimen (the surface that contacts with the dissipator through silicone grease) and the porous metal, we prepared two types of structure: an integrally formed seamless structure and a simply filled and pressed structure. As for the refrigerant, we used pure water with a flow rate of 0.1 L/min. The thermal resistance and pressure loss were calculated using the following Eqs. (1) to (3).

Thermal resistance $R = (Ts - Tw1)/Q$ ·········· (1)

Heat input $Q = c_w \cdot f \cdot (Tw2 - Tw1)$ ·········· (2)

Pressure loss $\Delta P = P1 - P2$ ····························· (3)

c_w : Specific heat of refrigerant, f : Flow rate of refrigerant
$P1$: Inlet pressure of refrigerant
$P2$: Outlet pressure of refrigerant

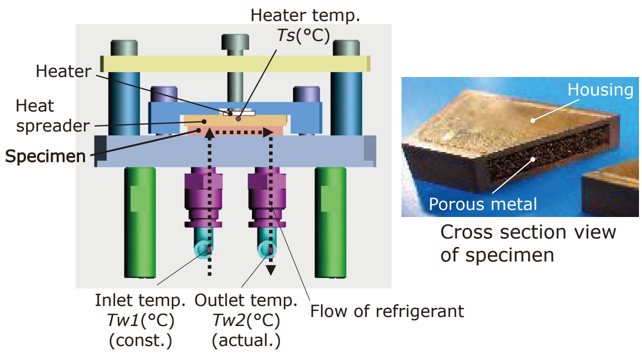


Fig. 1. Basic evaluation system of thermal resistance

Figure 2 shows the measurement results of the rising dissipator temperature after the heater is energized. The results show that when porous metal with a porosity of 80% is filled and integrally formed, the saturated temperature is 25°C lower than that when the dissipator has cavities, revealing that the dissipation performance is improved. The thermal resistance and pressure loss calculated using the evaluation results are shown in Fig. 3. The thermal resistance includes that of the silicone grease applied between the heat source and the housing specimen (about 0.2 K/W). Given that the thermal resistance is 1 when the dissipator has cavities, the measurement results of the thermal resistances, including that when the dissipator comprises pin fins, are plotted. When the prototyped porous metal is inserted, there is a clear difference in thermal resistance between the seamless-type dissipator (●) and the press-type dissipator (▲), and the effect of integral and seamless formation is significant. The thermal resistance is reduced by 25% at the maximum compared to that of a dissipator with pin fins, and by a staggering 60% at the maximum compared to that of a dissipator with cavities. If the arrangement of porous metal in the flow path can be optimally controlled to reduce the pressure loss, the cooling efficiency is expected to be improved compared to that of a dissipator with pin fins or cavities.

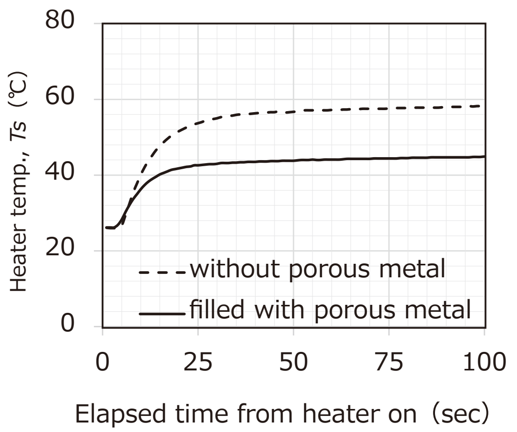


Fig. 2. Measurement results of dissipator temperature in Fig. 1

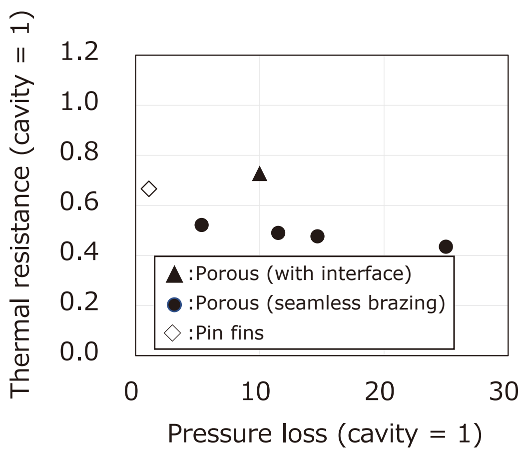


Fig. 3. Evaluation results of thermal resistance and pressure loss

3-2 Effects on loop heat pipes with the porous metal material

Then, we evaluated the effects on the loop heat pipes with the porous metal, a heat transfer device with no electricity.

Figure 4 shows the evaluation system for vapor-type loop heat pipes. A refrigerant (ethanol) in the space above wick of evaporation chamber is sucked by the capillary tube force to a wick made of pure aluminum porous metal (porosity: 60%), vaporizes with heat from a heating element attached to the bottom of evaporation chamber, moves through the groove, and radiates the heat. Heat is transferred to the condensor by the driving force of this increasing pressure and capillary tube force. This is the principle of vapor-type loop heat pipes.

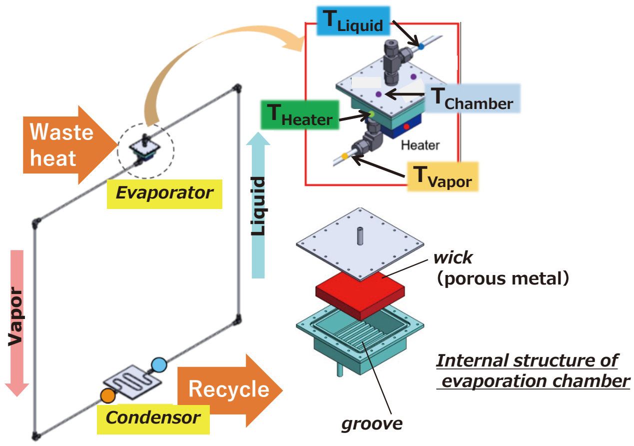


Fig. 4. Evaluation system for vapor-type loop heat pipes

Figure 5 shows the relationship between the vapor temperature, the reservoir tank water temperature, and the porous body temperature during operation with the heater energized to increase the heater block temperature. When the heater block temperature exceeds 80°C, the vapor pipe

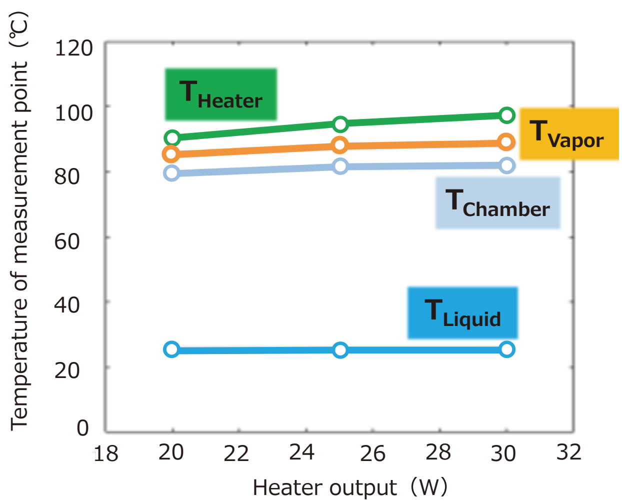


Fig. 5. Relationship between temperature of measurement points on the evaporator and heater output

temperature rises to about 70°C while the reservoir tank water temperature remains at 30°C or lower, showing that steady heat transfer is achieved. In addition, porous metal with a smaller pore diameter shows better performance. At that time, the calculated heat transfer coefficient exceeds 10,000 $W/m^2 \cdot K$, showing excellent heat dissipating performance.

Figure 6 shows the evaluation system for ferrofluid-type loop heat pipes. Ferrofluid-type loop heat pipes use temperature-sensitive ferrofluid as a refrigerant. It loses its magnetism when absorbing heat. In detail, low-temperature ferrofluid is attracted to a magnet placed in front of the heat source that heats the heater block. The ferrofluid then loses its magnetism while absorbing heat from the heat source, is no longer attracted, and is pushed out. This is the principle of heat transfer by ferrofluid-type loop heat pipes.

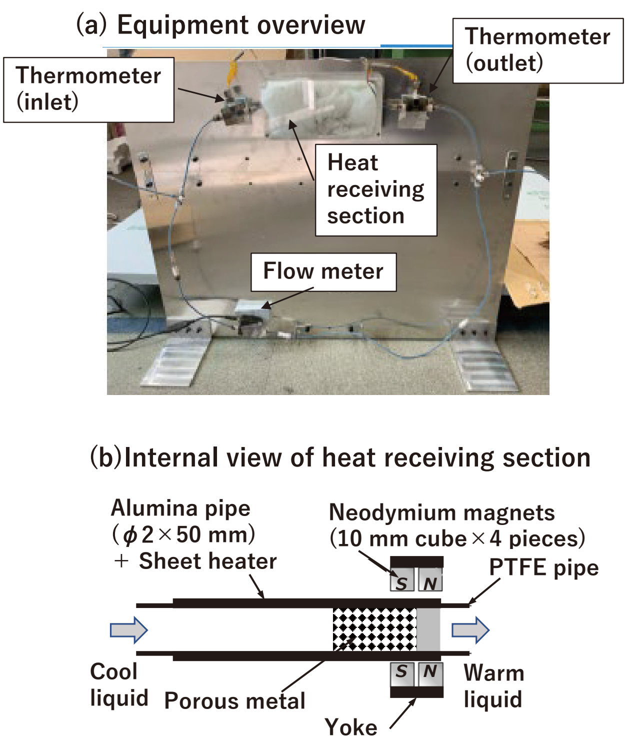


Fig. 6. Evaluation system for ferrofluid-type loop heat pipes

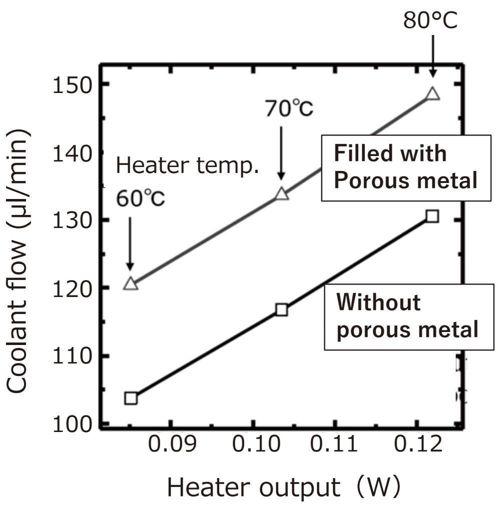


Fig. 7. Relationship between heater output and coolant flow

Figure 7 shows the relationship between the heater output and the coolant flow . The heater temperature drops when pure aluminum porous metal (porosity: 70%) is inserted, compared to that when porous metal is not used. In this application, changing the magnetism in the porous body can reduce the effects of the pressure loss.

3-3 Effects on heat storage devices with the porous metal material

For a heat storage device, we used pure aluminum porous metal (porosity: 70%) and paraffin with a melting point of 60°C as the heat storage material. We impregnated the porous metal with the melted paraffin heated to a temperature of around 100°C, which was sucked in by the capillary tube force. Then we cooled down the paraffin to solidify it inside the metal. The basic evaluation system for heat storage devices is shown in Fig. 8.

Figure 9 shows the behavior of the rising temperature after the heater is energized, comparing it to that when a simple aluminum plate is placed. When porous metal impregnated with paraffin is used, the temperature suddenly stops rising at around the melting point of the paraffin. Figure 10 shows the calculation results of apparent specific heats including latent heat when the paraffin melts. The specific heat of the porous metal material impregnated with paraffin is four times greater than that of pure metal, and the high heat conductivity of the porous metal material causes rapid and sweeping melting, resulting in a quick response.

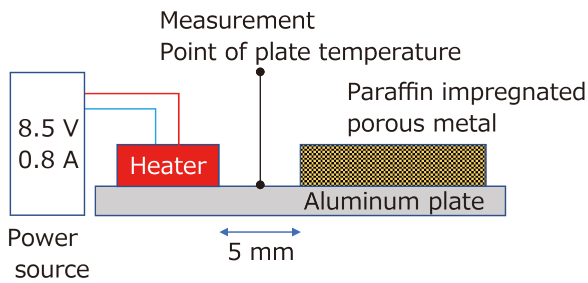


Fig. 8. Basic evaluation system for heat storage devices

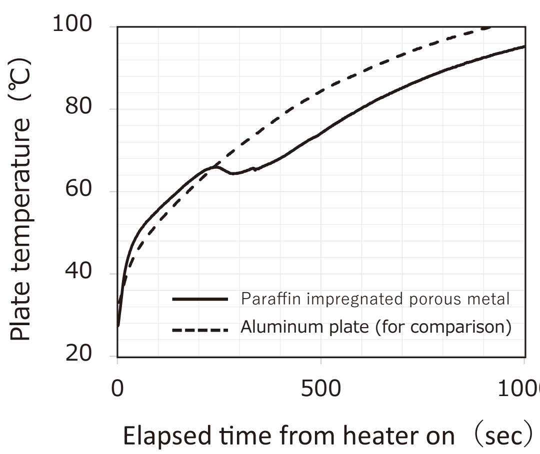


Fig. 9. Relationship between heater output and temperature in Fig. 8

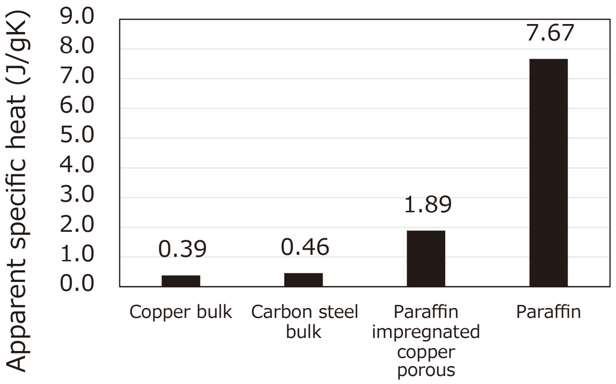


Fig. 10. Estimated value of apparent specific heat

4. Conclusion

Using our powder metallurgy process, we have developed a porous metal material featuring high thermal conductivity. On the assumption that it is used for thermal management, we conducted a basic evaluation of its performance in various heat- dissipating devices. The material is expected to be used to improve the performance of heat exchangers, loop heat pipes, and heat storage devices.

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Technical Terms

*1 Thermal conductivity: An indicator of how much heat a material can conduct. With higher thermal conductivity, the material conducts heat better and is useful as a heat-dissipating material.

*2 Powder metallurgy process: A process that involves mixing powdered metals, such as aluminum or copper, with powder additives (pore-forming agents), filling the mixture into a die heated to a specified temperature, and applying a pressure of 500 MPa or more by a press machine for compaction

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