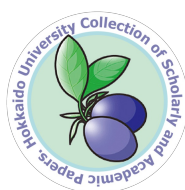




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Fabrication of Porous Transpiration-Cooling Device by Powder-Metallurgical Microchanneling Process

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Abstract

We propose the concept and fabrication method for a novel transpiration-cooling device. The device consists of an open-porous metal and contains microchannel networks. Cooling water is supplied from the tank to the every corner of the device through the microchannel networks and then seeps out to be vaporized absorbing the latent heat. The porous body of the device and the microchannel are produced by a powder-metallurgical microchanneling process. We investigate the influence of the porosity of the compact specimen on the seeping behavior of cooling water.

Key words

Microchannel, Powder Metallurgy, Transpiration Cooling, Copper, Porous Material

1. Introduction

The disaster preventing robot which works in a high-temperature environment requires advanced cooling technology for defending the internal electronic machine from heat. Transpiration cooling is starting to garner attention as such a technology [1]. Figure 1 shows a schema of the architecture of the disaster preventing robot previously proposed by Yano et al. [2]. The outer shell of the robot has a multi-tiered structure and consists of an outermost open-porous layer, an innermost solid layer and a water feed space between the two layers. Water is delivered via the feed space and then seeps out to the surface of the robot to be vaporized absorbing the latent heat of evaporation. This system makes it possible to protect the electronic device from the environmental heat efficiently. However, such a structure is difficult to design for parts with complicated geometries. In order to overcome this difficulty, we propose a novel transpiration-cooling method. Figure 2 illustrates the schema of this method. The shell of the robot consists of porous metal and contains microchannel networks which act as flow passages for the cooling water just as veins in plant leaves or blood vessels in animal bodies. And then the cooling water seeps out to the shell surface like sweat. The unique advantage of this method is that it unifies the space for feeding water and the porous layer into the shell of the robot. With this method, designing the robots will be easier. In order to produce such a porous device, we examined a powder-metallurgical microchanneling process [3-4]. Figure 3 illustrates the formation mechanism of the microchannel. In this process, two kinds of metals with different melting points are used: the body-metal, which has a higher melting point and is to compose the device body, and the sacrificial-core metal, which is to be fused and give the shape of the microchannel. Initially, body-metal powder containing a sacrificial core, a

shaped sacrificial-core metal, is prepared by unidirectional pressing. Subsequently, that powder compact is sintered at temperatures between the melting points of the metals. During sintering, molten sacrificial-core metal migrates to the body-metal region by infiltration and diffusion. As a result, a microchannel is formed at the sites initially occupied by the sacrificial-core metal. In addition, an alloy lining layer surrounding the microchannel often forms. We have confirmed that the microchannels are produced in various combinations of the metals. Particularly, we found that microchannels with clean-cut contours were produced when we used the combination of copper as the body metal and zinc as the sacrificial-core metal. In this study, we investigated the effects of the porosity of the compact specimen on the seeping behavior of water using the combination of copper and zinc as a model system to examine the feasibility of our novel transpiration-cooling system shown in Fig. 2.

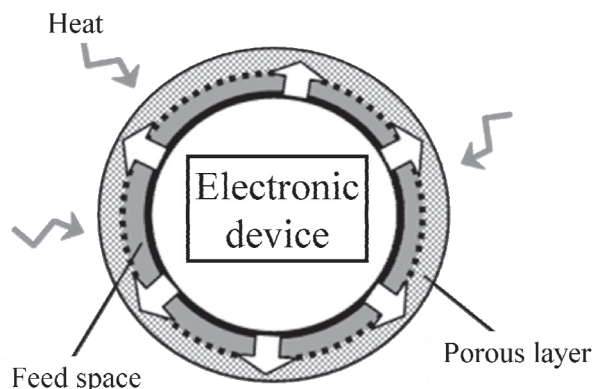


Fig. 1 Schema of the transpiration-cooling system for the disaster preventing robot [2]

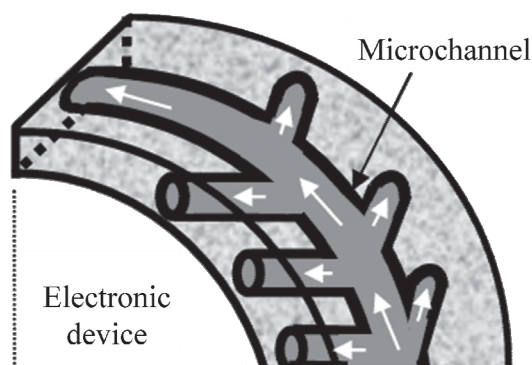


Fig. 2 Conceptual diagram for the novel transpiration-cooling method

2. Experimental Procedure

2.1 Powder compact

A cylindrical copper powder compact containing zinc wire was prepared by unidirectional pressing at room temperature. The mass of the copper powder was 18 g and the average diameter of the copper powder particles was 15 μm . A straight zinc wire 500 μm in diameter and 10 mm in length was used as the sacrificial core. The compacting pressures were varied from 20 to 300 MPa to controlling the porosities of the compact specimens. The obtained powder compact had a diameter of 20 mm, and a height of about 10 mm.

2.2 Heat treatment

The compact specimens heated at a constant rate of 0.2 K/s from room temperature to 1123 K, and then furnace-cooled at about 0.1 K/s. After sintering, the porosities of the sintered specimens were measured.

2.3 Water-flow examination

Figure 4 depicts the schematic illustration of the specimen for the flow examination. A 40-mm-long zinc wire was shaped into a zigzag configuration for the sacrificial core. The mass of the copper powder was 10 g. The obtained powder compact had a diameter of 20 mm, and a height of about 8 mm. After sintering, both ends of the microchannel were exposed, and the one end was connected with a copper pipe 1 mm in inner diameter. The copper pipe and the specimen were joined with an epoxy adhesive bond. Water was injected into the microchannel through the copper pipe. The flow rate of water was $2.5 \times 10^{-6} \text{ m}^3/\text{s}$. Behaviors of the water jet from the outlet of the microchannel and seeping water on the surface of the specimen were observed.

3. Results

3.1 Influence of the compacting pressure on the average porosity of the specimen and the lining-layer structure

Figure 5 shows the relationship between the compacting pressure and the average porosities of the powder compacts before and after sintering. Both average porosities decreased monotonously as the compacting pressure increased. Therefore, the average porosity of the transpiration-cooling device can be controlled by the compacting pressure. In the following, "the porosity" indicates that after sintering unless otherwise noted.

Figure 6 shows a back-scattered electron image of the cross-sectional structure near the microchannel. The microchannel contour and the lining layer are clearly shown in this photograph. In this study, similar apparent microchannels and lining layers were produced in all specimens. Figures 7(a), (b) and (c) present optical micrographs showing the formation of microchannels and lining layers in the sintered specimens compacted under 30, 80 and 156 MPa, respectively. In Fig. 7, the porosity of the lining layer and the body-metal region increased with decreasing compacting pressure.

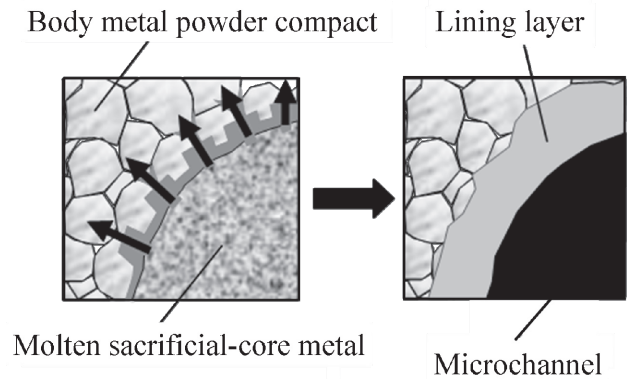


Fig. 3 Schematic illustration of the concept of the powder-metallurgical microchanneling process

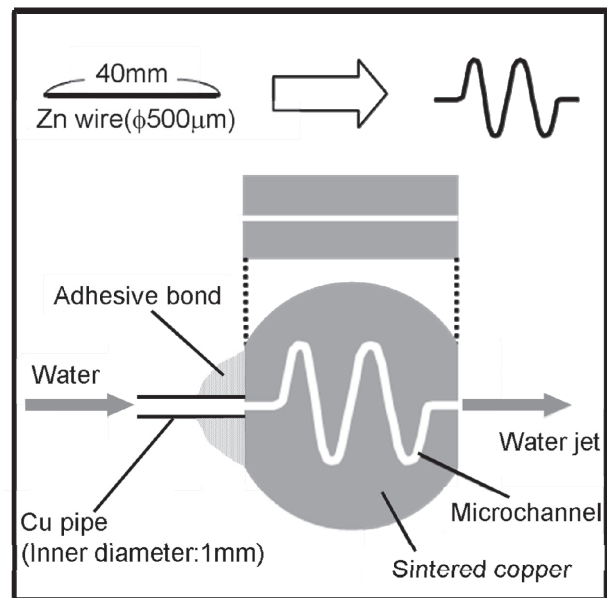


Fig. 4 Schema of the specimen for the flow examination

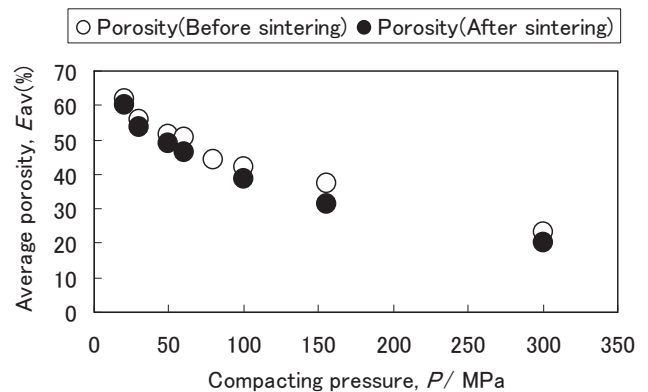


Fig. 5 Effects of the compacting pressure on the average porosities of the powder compacts before and after sintering

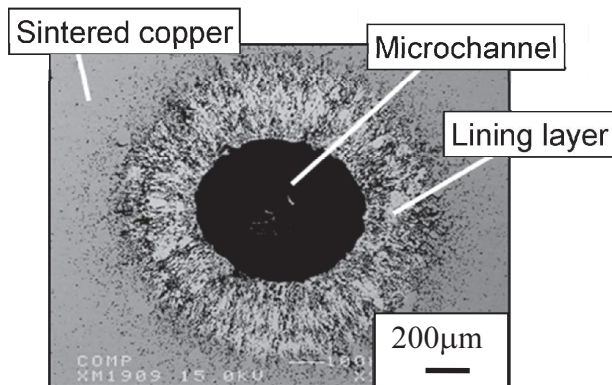


Fig. 6 Back-scattered electron image of a typical structure near the microchannel. The average porosity of the green compact: 31.3 %

3.2 Result of water-flow examination

Figure 8 shows the result of the water-flow examination for the specimen with the porosity of 53.5 %. A water jet from outlet of the microchannel and seeping water at the surface of the specimen were observed: This indicates that the microchannel was open throughout the length and our concept of the transpiration-cooling device is realizable. However, the seeping water was observed only at the lateral face of the columnar specimen but at the base end surfaces.

3.3 Influence of the porosity distribution on the water-seeping behavior

In order to find out why the seeping behavior of the water varied with the location on the specimen, the porosity distribution was measured in a specimen, which has a straight microchannel and the same porosity as the specimen shown in Fig. 8. The relationship between the porosity distribution and the seeping behavior was investigated based on percolation theory [5]. Percolation theory is stochastic theory for analyzing widespread phenomenon, for example, conductance of composites materials and the spread of mountain fire. According to this theory, the porosity, E , higher than 30 % is necessary for infiltration of water in three-dimensional porous media.

Figure 9 shows a schema of the specimen for measuring the porosity distribution. In order to show the influence of the lining-layer formation on the porosity distribution, a nylon wire with a diameter of 520 μm was also embedded in the specimen as a comparative sacrificial core. Figure 10 depicts the optical micrograph showing the formation of a microchannel by using the nylon sacrificial core. The microchannel was formed by the evaporation of nylon wire. Therefore, no lining layer formed around the microchannel. The porosity distribution was measured along the three lines illustrated in Fig. 9: the x -axis (the line A) and two lines parallel to the y -axis and passing through the respective centers of the microchannels (the lines B and C). The porosity distributions in the specimen were measured by image analysis on optical micrographs. The measured area at each measurement position was 0.7 mm $\times$ 1.0 mm.

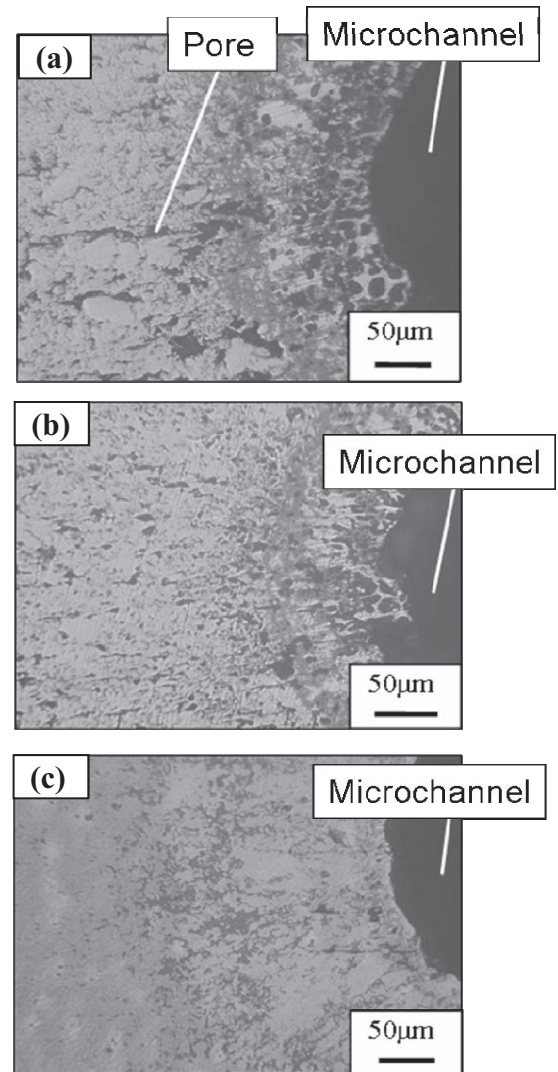


Fig. 7 Optical micrographs showing the formation of microchannels and lining layers in the specimens pressed under three kinds of pressures: (a) 30 MPa, (b) 80 MPa, (c) 156 MPa

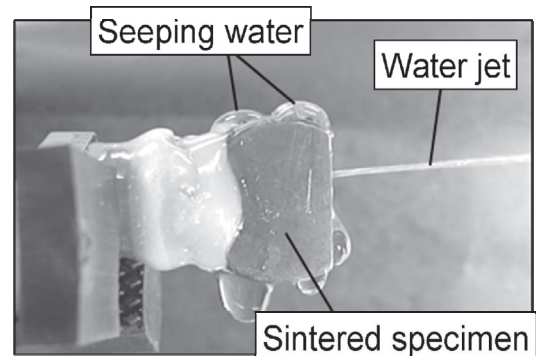


Fig. 8 Flow examination for the specimen pressed under 30 MPa

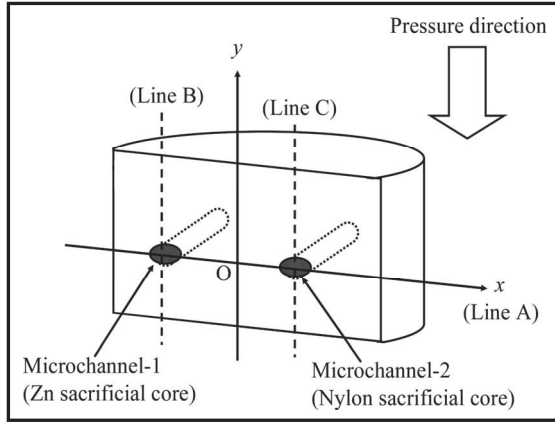


Fig. 9 Schema of the specimen for measuring the porosity distribution

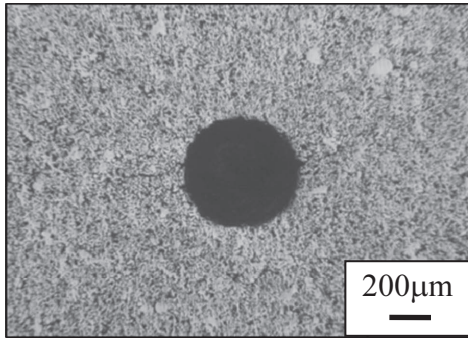


Fig. 10 Optical micrograph showing the formation of the microchannel at the site of the nylon sacrificial core. The compact specimen was pressed under 30 MPa

The porosity profile along the line A is shown in Fig. 11. The porosity is over 30 % for all plots. This result is consistent with the fact that the seeping water was observed at the lateral face of the specimen.

Figures 12 and 13 present the porosity profiles along the line B and C, respectively. In both cases, the porosity falls below 30 % near the base end surfaces. These results explain the reason why the seeping of water was not observed at these surfaces. Such a decrease of porosity near the base end surfaces may have caused by friction between the powder compact and the planes of the die base and the piston.

When comparing Figs. 12 and 13, it is also revealed that the lining layer in the case of the Zn sacrificial core did not obstruct water infiltration.

3.4 Influence of the compacting pressure on the water-seeping behavior

Figure 14 shows the result of the water-flow examination for the specimen with the average porosity of 31.9 %. A

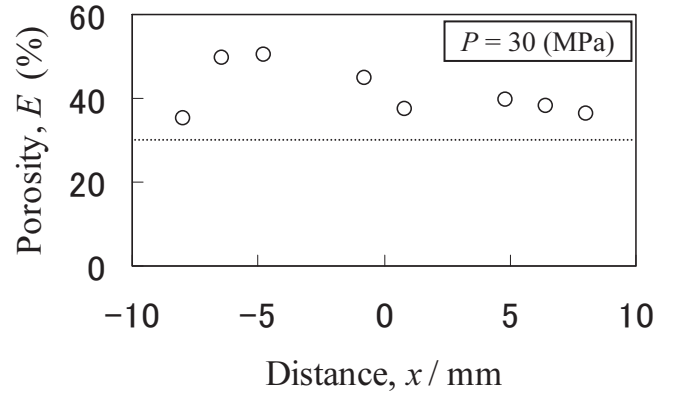


Fig.11 Porosity distribution along the line A ($y = 0$ mm)

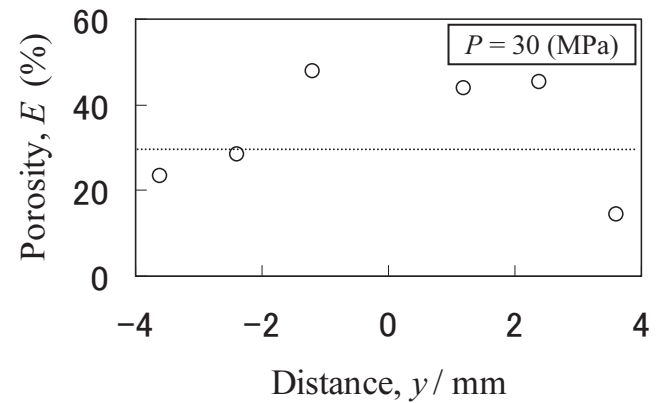


Fig.12 Porosity distribution along the line B ($x = -3$ mm)

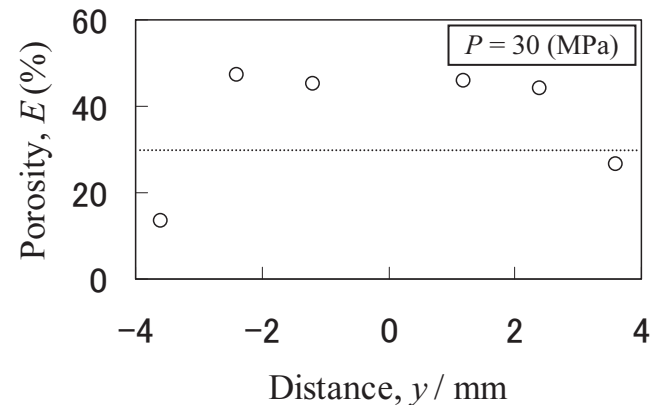


Fig.13 Porosity distribution along the line C ($x = 3$ mm)

water jet from the outlet of the microchannel was observed. However, the seeping water at the surface of the specimen was not observed. Figures 15, 16 and 17 depict the porosity distributions in the specimen pressed under the same pressure. In all cases, the porosity falls below 30 %. These results correspond to the fact that no seeping water was observed in the case of the specimen pressed under 156 MPa.

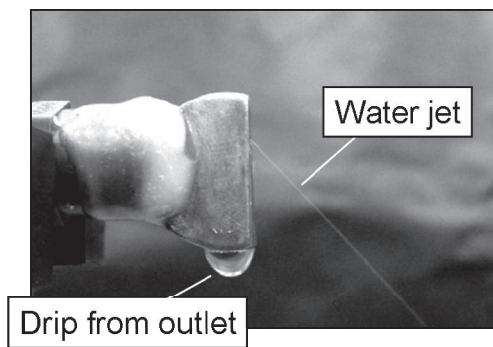


Fig. 14 Flow examination for the specimen pressed under 156 MPa

4. Conclusions

(1) The average porosity of the compact specimen can be controlled by the compacting pressure.

(2) Microchannels and lining layers were observed in all the specimens, which were pressed under 30-156 MPa.

(3) Seeping behavior of water was observed at the surface of the specimen pressed under 30 MPa. However, it was observed only at the lateral face of the columnar specimen but at the base end surfaces. The porosity fell below the critical percolation porosity, 30 % near the base end surfaces. This result explains the reason why the seeping of water was not observed at these surfaces.

(4) No seeping water was observed in the case of the specimen pressed under 156 MPa. All the porosity profiles were lower than the critical percolation porosity.

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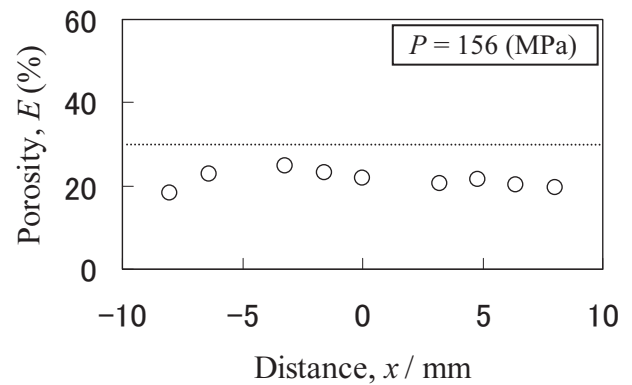


Fig.15 Porosity distribution along the line A ($y=0$ mm)

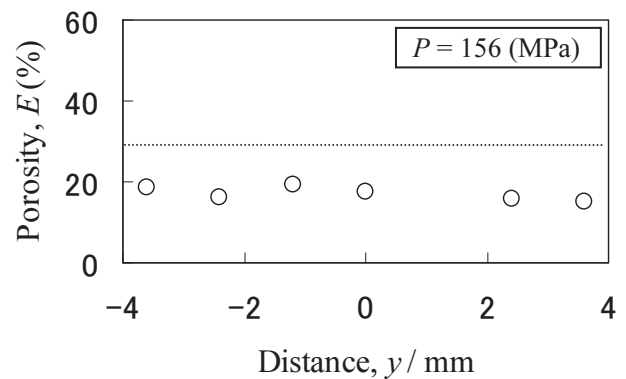


Fig.16 Porosity distribution along the line B ($x= -3$ mm)

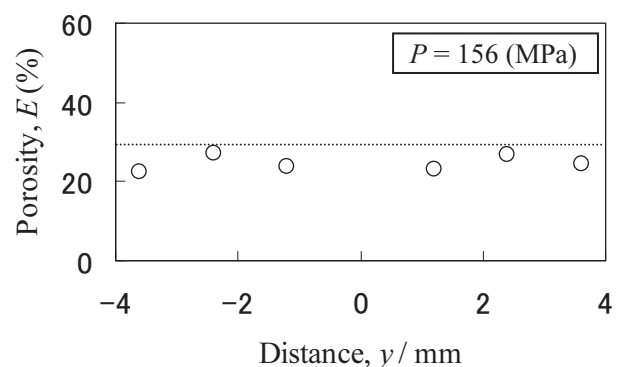


Fig.17 Porosity distribution along the line C ($x= 3$ mm)