Journal of JSEM, Vol.12, Special Issue (2012) s226-s231

Fabrication of Free-Form Channels by a combined process of Metal Injection Molding and Sacrificial-Core Method

Yutaro SHITARA[1], Tatsuya OHMI[2], Takehiko KUMAGAI[2] and Manabu IGUCHI[2]

[1] Graduate School of Engineering, Hokkaido University, Sapporo, Hokkaido 060-8628, Japan
[2] Faculty of Engineering, Hokkaido University, Sapporo, Hokkaido 060-8628, Japan

(*Received 10 December 2011; received in revised form 29 March 2012; accepted 26 April 2012*)

Abstract
A novel process has been examined to produce a free-form metal pipe containing thin channels. This process combined a sacrificial-core method and Metal Injection Molding (MIM). MIM compound containing SUS304 stainless steel powder was used as a body compound, and a compound with Cu powder was used as a sacrificial-core compound. These compounds were assembled and injection-molded, and then thermally treated for dewaxing and sintering. With an adequate heating treatment, the sacrificial-core metal migrated to the body-metal region, and thus a channel was successfully produced.

Key words
Microchannel, Powder Metallurgy, Metal Injection Molding, Infiltration, Stainless Steel, Copper

1. Introduction

A microchannel heatsink is a cooling device, which circulates a coolant through its closely-spaced microchannels. Since the microchannels have a high specific surface area, the heat source can be cooled effectively. Hence it is expected to be a sufficient cooling device for stand-alone robots or high heat-density micro-devices such as CPUs [1-2]. Some of the authors have investigated a powder metallurgical microchanneling process utilizing a sacrificial-core method to produce metallic microchannel devices [3-4]. In this process, two kinds of metals are used: a body metal and a sacrificial-core metal. The former has a higher melting point and is to compose a device body, and the latter is to flow out and give the shape of the microchannel. A body-metal compact containing a shaped sacrificial-core metal is sintered at a temperature between the melting points of these metals. The molten sacrificial-core metal migrates into the body metal powder region by infiltration or diffusion. Thus a microchannel can be formed directly in the body metal sinter. By using this process, we can produce three-dimensional microchannels from several combinations of metal powders as raw materials. We expect the process to realize a higher degree of freedom in the shape of the microchannel and a lower processing cost, compared to the conventional mechanical fabrication processes. However, this process has a difficulty to produce large-scaled metal members usable in actual situations. In addition, light metals such as Al and Mg, which have been used in various industrial products, are generally not suited for powder metallurgy.

In this paper, we propose a new method to produce a microchannel device in a light-metal member, that is, a combined method of Metal Injection Molding (MIM), sacrificial-core method and cast-in insertion [5-6].

Figure 1 shows the schema of the process. This process uses two kinds of compounds: a body compound which is a mixture of an organic binder and a body metal powder; and a sacrificial-core compound with a sacrificial-core metal powder. First, a long rod composed of the body compound and the sacrificial-core compound is produced by MIM as illustrated in Fig. 1. The rod is shaped to an intended configuration, and then thermally dewaxed and sintered. During sintering, the sacrificial-core metal melts and migrates into the body-metal region to form a microchannel. Finally, the pipe with a microchannel is cast-in inserted in a molten light metal such as Al or Mg, thereby a near-net-shape light metal member including a microchannel is produced. To materialize this set of processes, the free-form pipe fabrication process combining MIM and the sacrificial-core method should be established. As a first step of the study, we investigated channel formation in a specimen whose body part and sacrificial-core part are both composed of compounds.

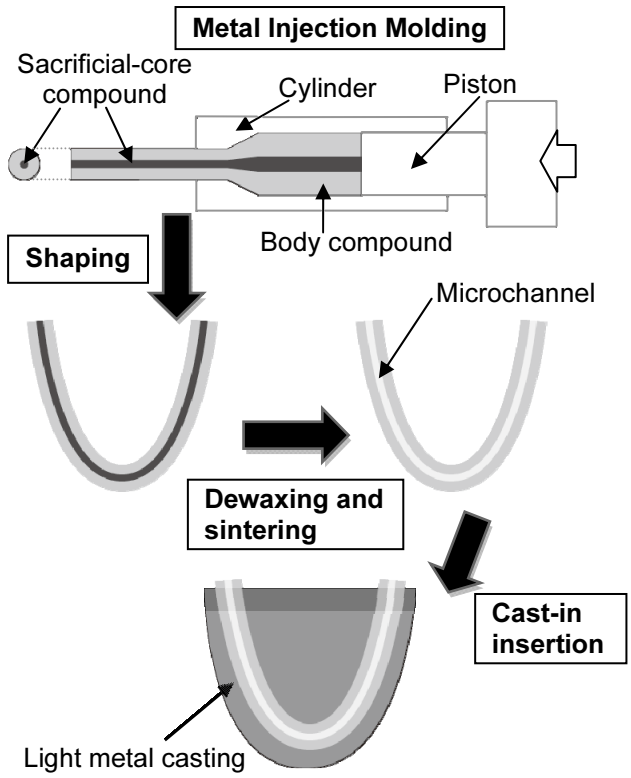

Fig. 1 Schema of the fabrication process for a free-form microchannel in a light metal body

2. Experimental Procedure

2.1 Preparation of compounds

Figure 2 shows a schematic of the MIM process for preparing the compound specimens. SUS304 powder (10 μm in average diameter) was used as a component of the body compound and Cu powder (15 μm in average diameter) was used for the sacrificial-core compound. Each powder was mixed with an organic binder in equal volume to prepare the compounds. The organic binder was prepared from yellow wax and pine resin blended in a mass ratio of 1:1. Each compound was injection-molded with a piston-type injection molding machine to form a columnar compound of 5 mm in diameter. These compounds were assembled and again injection-molded with the same machine, thus a rod-like specimen was produced. In the rod-like specimen, a Cu-compound core was involved in the SUS304 compound.

2.2 Heat treatments

After the MIM process, the rod-like specimen was cut into short columnar forms about 10 mm in length and then heat-treated under an Ar atmosphere. The heating patterns are shown in Fig. 3. The holding time between 2.13 ks and 9.33 ks corresponds to the thermal dewaxing process to clear the organic binder from the specimens.

Patterns (1), (2) and (3) were used to investigate an adequate heating condition for channel formation. Patterns (a) and (b) were used to observe behaviors of Cu during heat treatments. In Pattern (a), the specimen was quenched just after dewaxing. In Pattern (b), it was quenched at 1373 K, just above the melting point of Cu. The quenching operation was carried out by dipping in a molten Wood's metal.

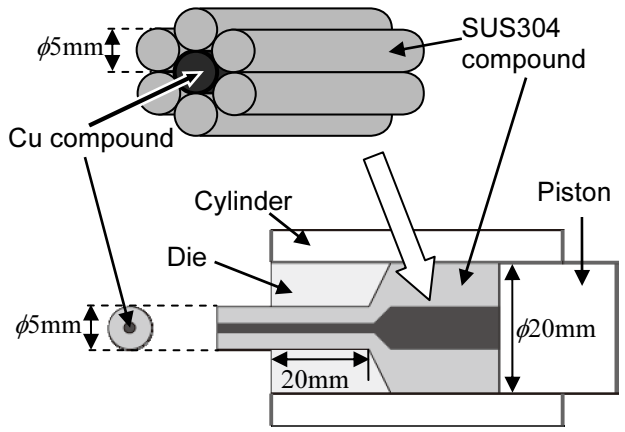

Fig. 2 Schematic illustration of the MIM process

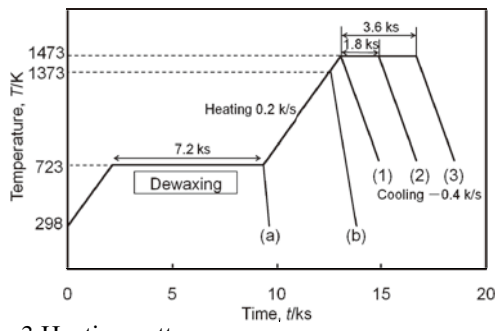

Fig. 3 Heating patterns

2.3 Model experiments on Cu infiltration

We also carried out model experiments to investigate the influence of the organic binder and its decomposition products on the infiltration behavior of liquid Cu into powder SUS304 region.

We used a drop method. Fig. 4 presents a schematic of the specimen used in this experiment. A Cu block (purity 99 %) was put on the top surface of a columnar SUS304 base. We used three kinds of SUS304 bases listed in Table 1. The base A was used to check wettability between liquid Cu and solid SUS304. The base B was composed of a dewaxed SUS304 compound to examine the influence of the decomposition products from the organic binder on the infiltration behavior of Cu. The base C, also made from the SUS304 compound, had been dewaxed and held at 1473 K for 3.6 ks to demonstrate the effect of temperature holding above the melting point of Cu. Each model experiment was heat-treated with the same pattern as Pattern (1) but without dewaxing.

2.4 Fabrication of bend pipe

The rod-like compound was shaped into a bend form illustrated in Fig. 5. The bend angle, θ, was 90° and the curvature radius, R_a, was 12 mm. The compound was heat-treated in the adequate heating pattern obtained from foregoing experiments. After heat treatment, a flow examination was conducted for the specimen to investigate penetration of the channel.

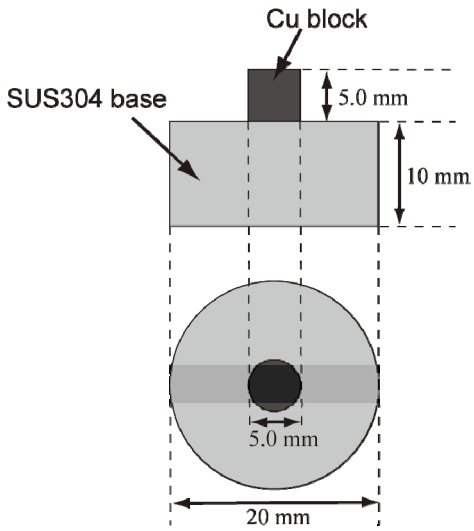

Fig. 4 Schematic of the specimen for the model experiment on the infiltration behavior of liquid Cu into powder SUS304 region

Table 1 Materials for the SUS304 bases in the drop method experiment

Base	Material
A	SUS304 powder compact (porosity 50 %)
B	SUS304 compound only dewaxed
C	SUS304 compound dewaxed and heat-treated

3. Results and Discussion

3.1 Injection-molded specimen

Figure 6 shows an external apparatus and cross section of an injection-molded specimen prepared by the MIM process in Fig. 2. In this specimen, a SUS304 body compound about 50 mm in length and 5 mm in diameter included a continuous Cu sacrificial-core compound. The intended diameter of the sacrificial core was 1.25 mm. However, the actual diameter was often larger than intended: less than or equal to 2.0 mm. This was attributed to the fact that the compound flow near the circumference was slower than that near the center during injection molding.

3.2 Formation of thin channels

Figure 7 shows structures near the sacrificial-core part in the specimens heat-treated with Patterns (1), (2) and (3) illustrated in Fig. 3. In Fig. 7 (a), the Cu phase still retained at the site of the sacrificial core. In Fig. 7 (b), a cavity was observed. The channel might be going to penetrate. However, infiltration of Cu into the SUS304 region was not completed. In Fig. 7 (c), the channel had been completed. These results indicate that temperature-holding above the melting point of Cu is a significant operation for producing the channel.

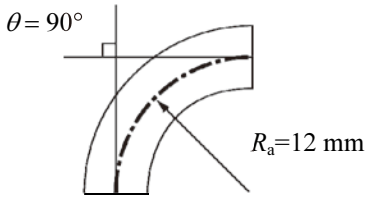

Fig. 5 Configuration of the bend compound

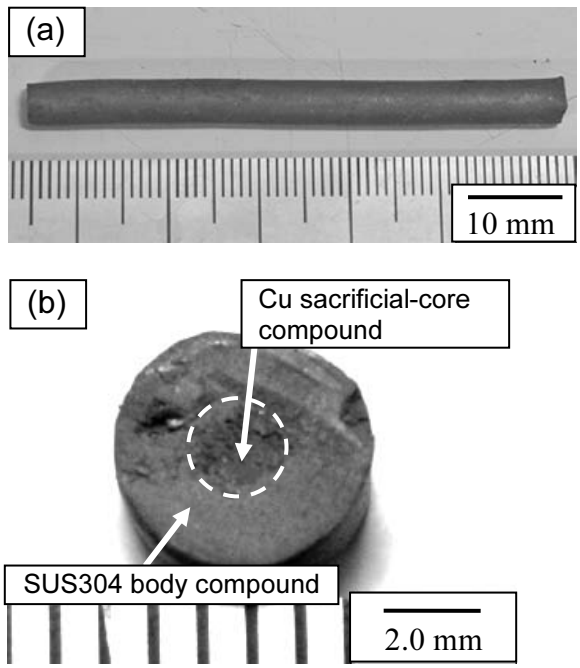

Fig. 6 Injection-molded specimen
(a) Outline view, (b) Cross-sectional view

3.3 Behavior of Cu before the temperature holding

In order to clarify the behavior of Cu before the temperature holding, structures of the specimens produced with Patterns (a) and (b) were examined.

Figure 8 presents the structure of the specimen heat-treated with Pattern (a). The specimen was quenched just after thermal dewaxing. The white broken line in the figure indicates the boundary between the SUS304 region and the Cu region. In this specimen, networks of partially sintered powder particles were observed in each metal region. In both regions, carbon was detected by EPMA. Decomposition products from the organic binder, mainly composed of C, have been adsorbed on the surface of the powder particles.

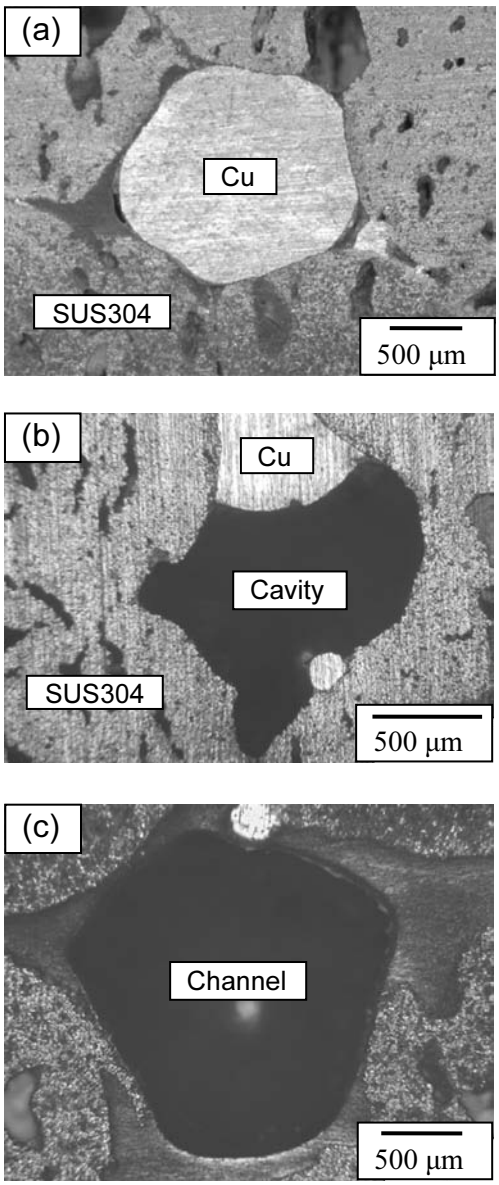

Fig. 7 Structures near the sacrificial-core part in the specimens heat-treated with various heating patterns
(a) Pattern (1): 0 s holding at 1473 K
(b) Pattern (2): 1.8 ks holding at 1473 K
(c) Pattern (3): 3.6 ks holding at 1473 K

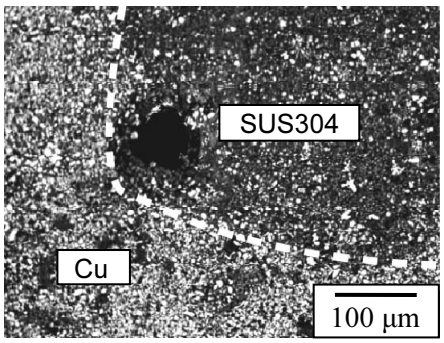

Fig. 8 Back-scattered electron image near the boundary between the SUS304 region and the Cu region in the specimen heat-treated with Pattern (a)

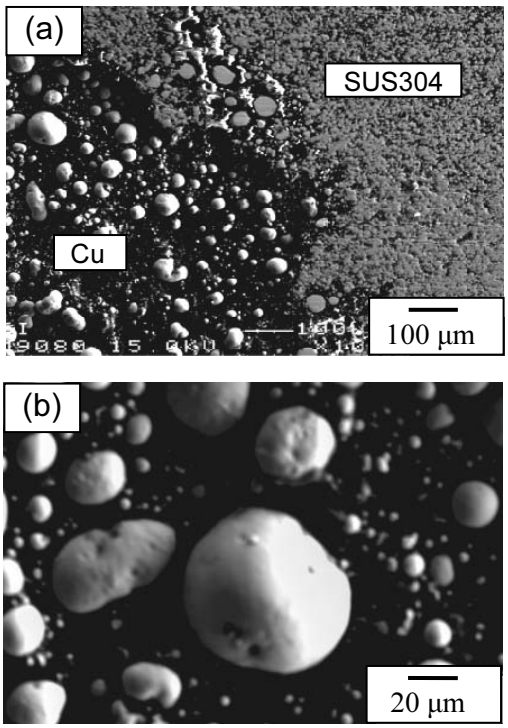

Fig. 9 Back-scattered electron image near the boundary between the SUS304 region and the Cu region (a) and a magnified view of the Cu spheres (b) in the specimen heat-treated with Pattern (b)

Figure 9 depicts the specimen quenched at 1373 K (Pattern (b)). In this specimen, spheroidizing of the agglomerated Cu particles was observed. Formation of small spheres of the sacrificial-core metal is a characteristic phenomenon occurred in the case of the sacrificial-core compound. In fact, some of the authors reported that infiltration of Cu occurred immediately after Cu melting when they used Fe powder as the body-metal powder and Cu wire as the sacrificial core [7]. This is mainly due to the good wettability between liquid Cu and solid Fe [8]. SUS304 also has a good wettability against liquid Cu. In contrast, Fig. 9 and Fig. 7 (a) indicate that liquid Cu remained in the original site for a long time in our process. We speculated that the delay of liquid Cu infiltration had been caused by decomposition products from the organic binder.

3.4 Wettability between liquid Cu and dewaxed SUS304 compound

Figures 10, 11 and 12 provide the cross-sectional structures of the specimens with SUS304 bases A, B and C, respectively. In Fig. 10 (a), the Cu block on the base completely disappeared, and Cu was dispersed uniformly in the SUS304 compact as shown in Fig. 10 (b). This indicates that liquid Cu infiltrated into the SUS304 base immediately after Cu melting because of the good wettability between them.

In Fig. 11 (a), a solidified Cu drop retained on the SUS304 base. In this specimen, the Cu drop was not joined with the SUS304 base. In the magnified view presented in Fig. 11 (b), a dark layer existed on the surface of the SUS304 base. This layer probably contained the decomposition products from the organic binder and this result shows that the decomposition products were an obstacle to infiltration of liquid Cu.

In Fig. 12 (a), the most part of the Cu drop remained on the base. However, the Cu drop was joined with the base, and the dark layer observed in Fig. 11 (b) did not appear in this specimen as shown in Fig. 12 (b). This result therefore describes the restoration of the wettability on the surface part of the base. In addition, infiltration of Cu was observed in the relatively-large pores near the surface of the base. These results suggest that the temperature holding above the melting point of Cu caused the diffusion of the contamination on the surface of the SUS304 powders and restore the wettability between liquid Cu and solid SUS304.

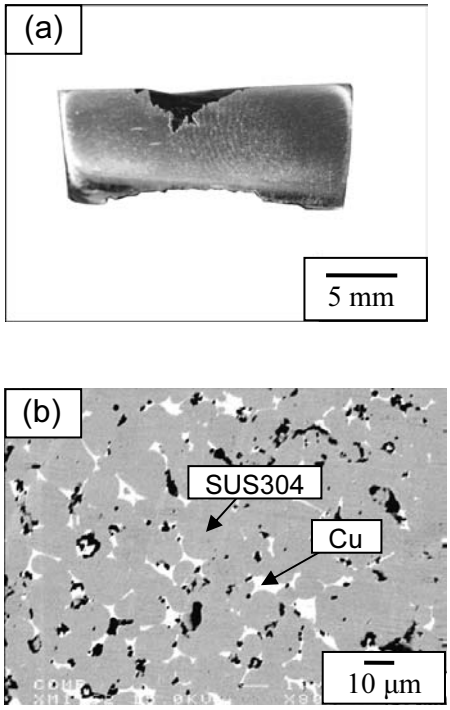

Fig. 10 Macroscopic cross-sectional structure (a) and back-scattered electron image of the microstructure (b) of the specimen with SUS304 base A

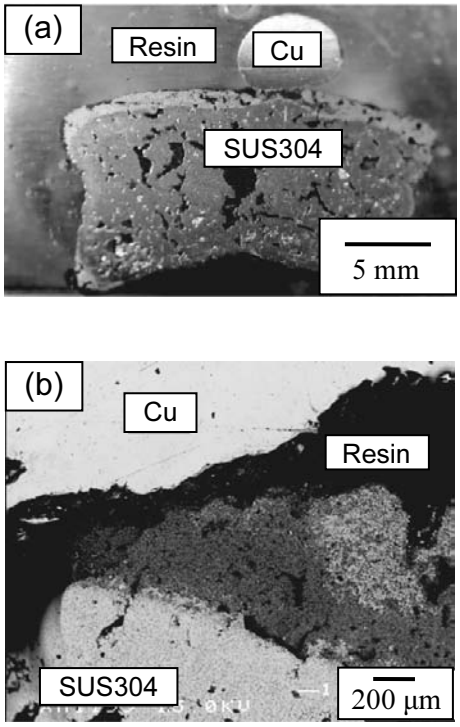

Fig. 11 Macroscopic cross-sectional structure (a) and back-scattered electron image of the microstructure (b) of the specimen with SUS304 base B

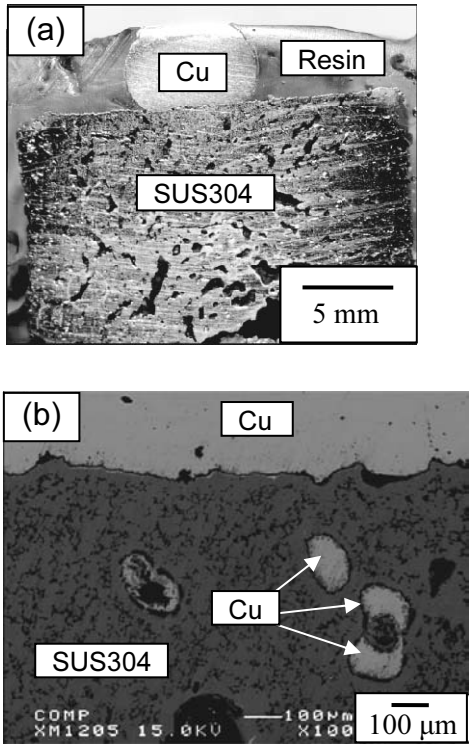

Fig. 12 Macroscopic cross-sectional structure (a) and back-scattered electron image of the microstructure (b) of the specimen with SUS304 base C

3.5 Channel formation mechanism

From the results above, the channel formation can be systematically summarized as follows with the schematic illustrations in Fig. 13.

In the initial stage of the process, the powder particles of each metal had been dispersed uniformly in the organic binder (see Fig. 13 (a)). After thermal dewaxing process, the networks of partially sintered powder particles were formed in each metal region, and the decomposition products from the organic binder, mainly C, were concurrently adsorbed on the surface of powder particles (see Fig. 13 (b)). These contaminations were going to change the wettability between liquid Cu and SUS304 from good to poor. During the heating treatment after the dewaxing process, the partially sintered fine Cu particles got together with adjacent particles, and then formed the droplets at a temperature above the melting point of Cu, as present in Fig. 9 (b) (see Fig. 13 (c)) However, the infiltration was disturbed by the decomposition products from the organic binder. In addition, sintering of the SUS 304 powder also progressed in parallel. This is the reason the infiltration did not occur at the onset of Cu melting. Finally, during temperature holding, the decomposition products diffused into inside of the body metal, and this caused the restoration of the wettability. From this point forward, the liquid Cu started infiltration, whereas the narrow paths favorable for the infiltration was changing to close pores (see Fig. 13 (d)).

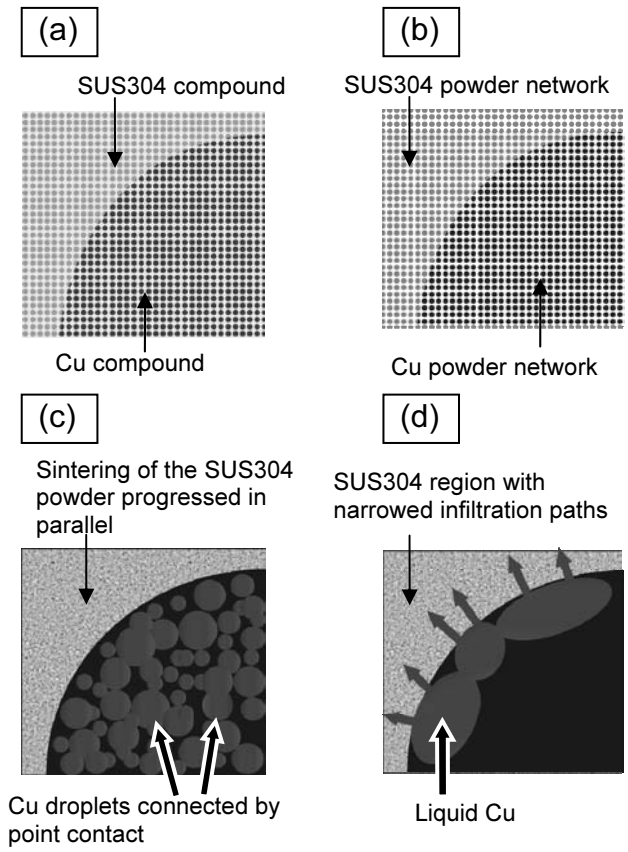

Fig. 13 Schematic illustrations of the channel formation mechanism in our process: (a) Initial stage, (b) Stage after the thermal dewaxing, (c) Sintering stage, (d) Temperature-holding stage

Thus the restoration of wettability and the blockage of the infiltration path were two contradictory factors which governed the infiltration. In order to produce the channel certainly, the infiltration of Cu should occur before the infiltration paths in the SUS304 region close by sintering. Hence the contaminations generated from the organic binder, which would be the obstacle for the infiltration, should be minimized. In other words, it is possible to put our process into practical use by adopting an appropriate binder and dewaxing method.

3.6 Production of bend specimen

Figure 14 shows appearance of the bend specimen before and after heat treatment. Between the two specimens, differences in the shape and the dimensions were not observed. In addition, prominent collapses or cracks did not appear in the sintered specimen. This indicates that the sintered body with the intended shape was able to be produced from the rod-like compound produced by injection molding.

Figure 15 shows the flow examination for the sintered specimen depicted in Fig. 14 (b). Water was delivered to the downside of the specimen through a plastic tube with a syringe. The flow rate was 2.6×10^{-6} m^3/s. In the flow examination, a water jet from the outlet of the channel was observed, and therefore penetration of the bend channel in the specimen was confirmed. These results suggest that the small bend pipe containing the thin channel was fabricated with the combining process of MIM and the sacrificial-core method.

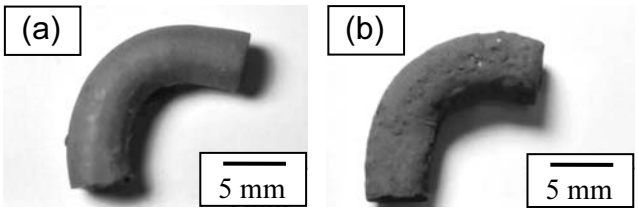

Fig. 14 External view of the bend specimen
(a) Before heat treatment, (b) After heat treatment

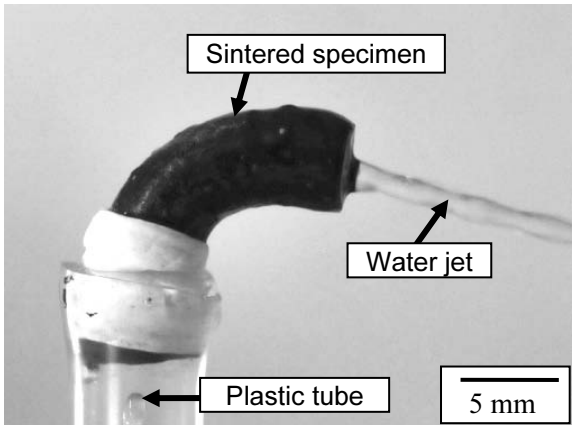

Fig. 15 Flow examination for the sintered specimen

4. Conclusion

We have investigated the novel process combining MIM and the sacrificial-core method to fabricate free-form pipes containing thin channels. We used a SUS304 compound as the body compound and a Cu compound as the sacrificial-core compound. The results are summarized as follows.

(1) Formation of a thin channel was confirmed in the specimen held at 1473 K for 3.6 ks. On the other hand, the infiltration of the Cu into SUS304 region was not completed in the specimens held at 1473 K for 1.8 ks and 0 s.

(2) The delay of the channel formation was caused by the decomposition products from the organic binder in the compounds.

(3) A small bend pipe containing a thin channel was fabricated by using our process combining MIM and the sacrificial-core method.

References

[1] Yano, T., Imai, R. and Isomura, K.: Thermalhydraulics in Micro-channel, Journal of Japan Society of Fluid Mechanics, 21 (2002), 55-61

[2] Omura, M., Ohmi, T., Kumagai, T. and Iguchi, M.: Fabrication of Porous Transpiration-Cooling Device by Powder-Metallurgical Microchanneling Process, *J. JSEM Special Issue*, **10** (2010), 205-209.

[3] Ohmi, T., Takatoo, M., Iguchi, M., Matsuura, K. and Kudoh, M.: Fabrication Process for Metallic Microchannel Devices for High-Temperature Use (in Japanese), *J. JSEM*, **5**-3 (2005), 234-238.

[4] Ohmi, T., Takatoo, M. and Iguchi, M.: Powder-Metallurgical Free-Form Microchanneling Process for Producing Metallic Microreactors, *J. JSEM Special Issue*, **9** (2009), 125-129.

[5] Ho, W, P., Li, F, Q. and Fuh, Y, H, J.: Evaluation of W–Cu metal matrix composites produced by powder injection molding and liquid infiltration, *Materials Science and Engineering A*, **485** (2008), 657-663.

[6] Ohmi, T., Sakurai, M. and Iguchi, M.: Microchannel Formation in Metallic Wire Bundles by a Sacrificial-Core Method, *Proc. 5th International Symposium on Advanced Science and Technology in Experimental Mechanics*, (2010) (CD-ROM)

[7] Kodama, T., Ohmi, T. and Iguchi, M.: Microchanneling and Lining Layer Formation by Spontaneous Infiltration in Fe-Cu System, *J. JSEM Special Issue*, **10** (2010), 199-204.

[8] Takahira, N. and Tanaka, T.: Unusual Wetting of Liquid In and Cu on Iron Substrate treated with Oxidization-Reduction Process (in Japanese), *Netsu Bussei*, **20**-2(2006), 70-74.