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Computational Analysis of the Compaction Fabrication Process of Composite Unidirectional Cellular Metals

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Abstract

Cellular structures have attracted wide attention as structural materials that are light and strong. Consequently, numerous previous cellular structures have been fabricated using a single metal as the base material owing to the complexity of the fabrication method; however, studies on the fabrication of multimaterial cellular structures are rather limited. In this study, we computationally analyse the fabrication process of two types of copper/stainless-steel composite unidirectional porous (UniPore) structures with a stainless-steel cover layer on the entire inner surface of the copper pipe to identify the conditions of the experimentally fabricated UniPore structures using the explosive compression method. Our results regarding the collision velocity of the metals during compression and the temperature at the time of collision indicate that wider gaps are required between the metals to increase the collision velocity between the metals and that pipe hardness decreases during collisions due to temperatures reaching the metal's melting point.

1. INTRODUCTION

To improve the sustainability and environmental performance of transportation equipment, structural materials used for such equipment must be lighter and stronger. To this end, various technologies have been developed for the production of light and strong materials. In this regard, cellular structures have attracted wide attention [1–3]. Notably, casting, solidification, sintering, and additive manufacturing have been used for manufacturing cellular metals [4–8]. Compared with conventionally used dense materials, cellular materials are strong yet have a low weight. They present a high stiffness to weight ratio and are good impact absorbers during collisions. For instance, the classic honeycomb sandwich plate structure has been widely employed as an impact absorber in several fields due to its excellent energy absorption capacity, high specific stiffness, and strength. Consequently, various studies have been conducted on its mechanical properties [8–11]. Particularly, Hokomoto et al. used an explosion–compression technique to explain the fabrication process of a unidirectional porous (UniPore) structure, which could be fabricated with long lengths, along with the mechanical properties of the cellular material, such as compression, bending, and heat exchange properties[12–14].

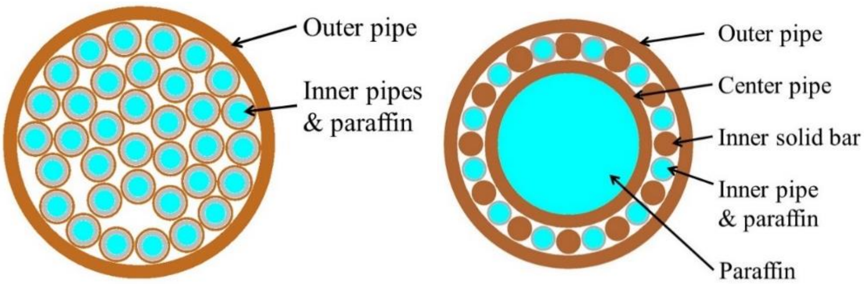
Numerous previous cellular structures have been fabricated with a single metal as the base material due to the complexity of the fabrication method; however, studies on the fabrication of multimaterial cellular structures are rather limited. A multimaterial refers to the combination of multiple materials with different properties, rather than a single material. The fabrication of multimaterials aims to satisfy sophisticated and diversified needs by combining multiple materials with different properties when the desired function cannot be achieved with a single material. In this regard, applicable joining methods include brazing such as resistance spot welding, friction stir welding, friction stir spot welding, and mechanical fastening of rivets[15–18]. In a previous study, we combined the high thermal conductivity of copper with the corrosion and high-temperature resistance of stainless steel using explosion-welding techniques[19–22]. Consequently, two types of copper/stainless-steel composite UniPore structures with a stainless-steel cover layer over the entire inner surface of the copper pipe were fabricated, and their performance was evaluated [23]. Notably, such multimaterial cellular materials are expected to be used in heat exchange and piping applications, as well as in enhancing impact resistance in high-speed collisions.

Typically, dissimilar materials need to be joined or bonded to fabricate multimaterials; however, the joining and bonding processes represent the major challenges. A similar issue is encountered when fabricating multimaterial cellular materials using the explosion–compression technique proposed by the authors; moreover, visualisation during the experiment [23] is difficult because deformation proceeds inside the outer pipe. In this study, we used computational analysis to investigate the deformation mechanism and metal-to-metal bonding conditions during the fabrication process and compared the results with the experimental results of UniPore material fabrication.

2. COMPUTATIONAL SIMULATION INVESTIGATION

2.1 Sample Preparation

In a previous study [23], we produced two types of cellular materials. Figure 1 presents a schematic of the initial state of each sample cross-section; herein, the samples presented in Figure 1a and b are referred to as samples A and B, respectively. In Figure 1, brown denotes copper, silver denotes stainless-steel, and light blue denotes paraffin.



(a) Sample A (b) Sample B

Figure 1: Samples. Reprinted from [23].

The samples mentioned above belong to the category of cellular metals with longer and uniform unidirectional pores and have a UniPore structure, as proposed by Hokamoto et al., which is fabricated via the explosive compression of cylindrical copper pipe assemblies.

Sample A was a UniPore copper structure with a stainless-steel pipe inserted in the inner pipe to prevent corrosion. Paraffin was placed inside the stainless-steel pipe to prevent the pipe from closing completely during the compression process. This paraffin was melted and removed after the experiment. The dimensions and numbers of pipes used are listed in Table 1.

Table 1: Dimensions and composition of sample A

Component	Material	Outer Diameter (mm)	Inner Diameter (mm)	Number	Length (mm)
Outer pipe	Cu (JIS-C1220)	30	27	1	210
Inner pipe	Cu (JIS-C1220)	4.0	3.4	35	260
Inner pipe	Stainless-Steel 304	3.3	2.3	35	260

Sample B had a concentric structure comprising outer and central copper pipes. Solid copper rods and paraffin-filled stainless-steel pipes were arranged alternately in the space between the outer and central pipes. Table 2 lists the dimensions and composition of sample B.

Table 2: Dimensions and composition of sample B.

Component	**Material**	**Outer Diameter (mm)**	**Inner Diameter (mm)**	**Number**	**Length (mm)**
Outer pipe	Cu (JIS-C1220)	30	27	1	210
Centre pipe	Cu (JIS-C1220)	20	17	1	200
Inner solid bar	Cu (JIS-C1220)	3.0	-	12	200
Inner pipe	Stainless-Steel 304	3.0	2.4	12	200

2.2 Computational simulation setup

The cylindrical explosion welding method produces unidirectional-type cellular metals. Information on the experimental and manufacturing methods based on the principle of the cylindrical explosion welding method can be found elsewhere [14, 23].

In those analyses, computational simulations were performed using a two-dimensional planar model with a transverse cross-section of the experimentally fabricated UniPore assembly. Figure 2 depicts the computational analysis model. Here, samples A and B in Figure 1 were inserted into “Pipes” denoted in Figure 2. The basic analysis method, material model, and material parameters were the same as those described in [14, 24]. An objective of the current computational analysis was to acquire thermal information during compaction, which is known to affect multimaterial joints. Therefore, certain parts incorporate smoothed-particle hydrodynamics (SPH) elements, for which Langange/Langange interactions can be used, as in the computational analysis described in [14]. Here, the inner copper pipe in sample A, the outer and inner pipes, along with the inner solid bar, inner pipe, and paraffin in sample B, represent SPH elements.

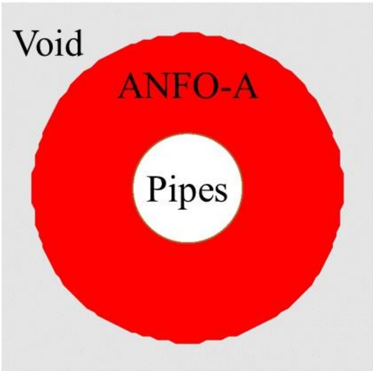


Figure 2: Two-dimensional computational model. Reprinted from [23].

The ANFO-A explosive, which is typically used for explosive pressure welding, was simulated using the Euler element. The pipes presented in Figure 1, which include metal pipes, metal rods, and paraffin, were inserted into "Pipes" in Figure 2. The boundary between the explosive and the pipes was analyzed using Euler-Lagrange interactions in ANSYS AUTODYN.

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3. RESULTS AND DISCUSSION: SAMPLE A

The recovered sample A had no cracks or wrinkles [23]. An enlarged cross-section of the sample polished during the etching process at the pipe joint is presented in Figure 3. We noticed that the pipes were firmly joined, with the exception of certain holes with a sharp shape and a few spots at which the copper and stainless-steel pipes were not welded. The Vickers hardness test conducted around the pipe joint revealed that the hardness of the molten part of the triple collision point located at the centre of the joint boundary was significantly reduced; however, at other locations, the hardness increased overall due to work hardening. Note that before explosive forming, the original hardness values of phosphor-deoxidised copper and stainless-steel were approximately HV 120 and HV 280, respectively.

Based on the information acquired during compression, including the impact velocity and impact pressure, we further examined these experimental findings using computer simulations.

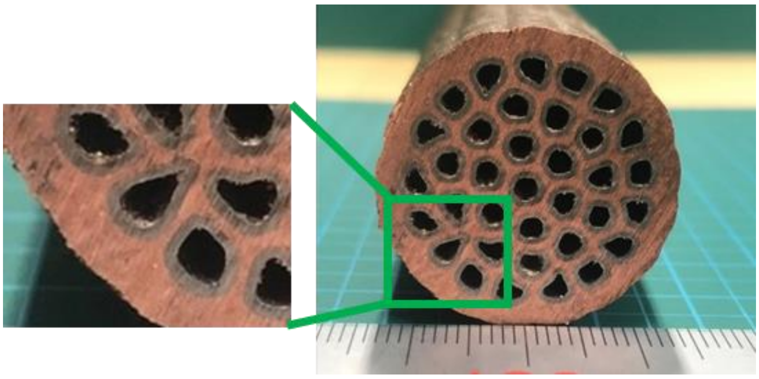

Figure 3: Transverse cross-section of sample A: final state form and enlarged view. Reprinted from [23].

i) The compression moulding process using computational analysis is illustrated in Figure 4. A gap can be observed between the inner pipes placed on the lower side in the initial configuration. In addition, the inner pipes are found to have been significantly deformed during moulding. The experimental results in Figure 4 reveal that some holes present a sharp shape.

This issue has also been discussed in another study [14]. Note that the hole shapes after moulding can be made uniform by ensuring that a large void is not created in the initial arrangement of the inner pipe.

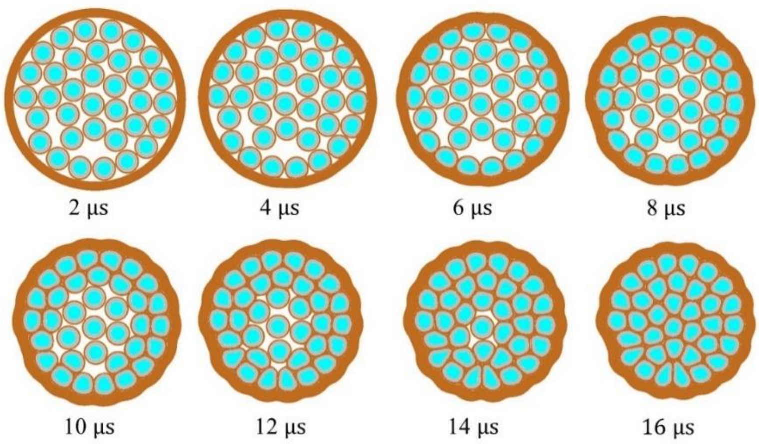

Figure 4: Compression forming process using the computational simulation (Explosive is not displayed)

ii) Notably, at a few places, the copper and stainless-steel pipes are not welded in Figure 5. Figure 6 presents the velocity history of the copper pipe that affected the inner stainless-steel pipe. This phenomenon was attributed to an insufficient velocity because the required minimum velocity of 200 m/s for explosion crimping could not be attained due to insufficient clearance between the copper and stainless-steel pipes.

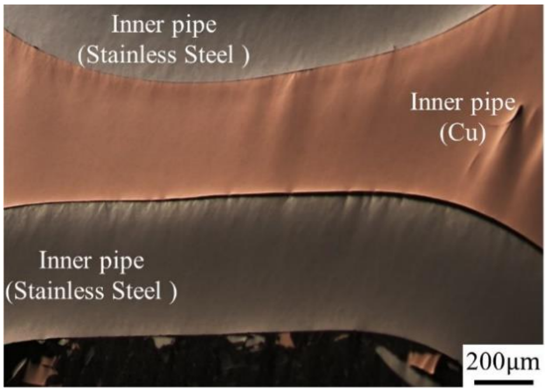

Figure 5: Magnified transversal cross-section of sample A. Reprinted from [23].

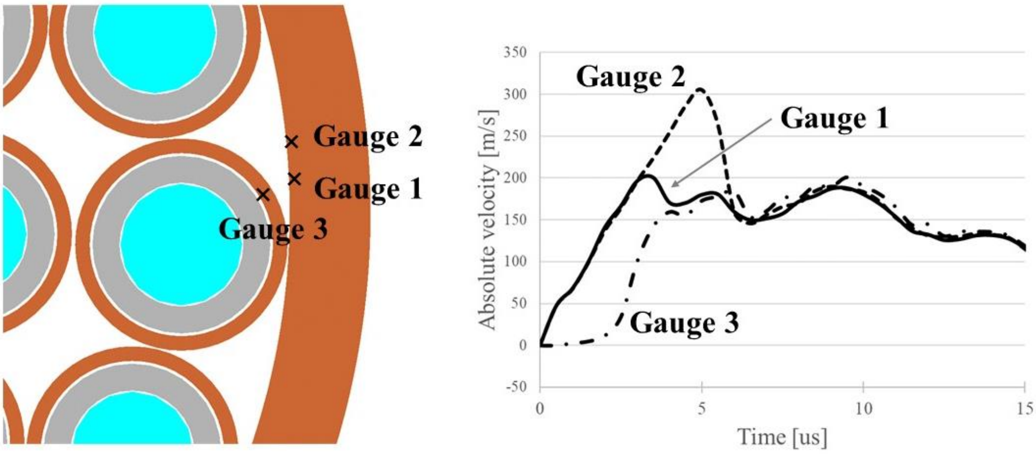

Figure 6: Velocity history of copper pipes.

iii) Figure 7 indicates that the hardness decreased significantly in the molten area at the triple collision point (collision point between the inner pipes) located at the centre of the joint boundary. Figures 8 and 9 present the pressure and temperature, respectively, at the triple impact point. This phenomenon in Figure 7 has been considered to indicate the occurrence of a metal jet since this sample utilises the technique of explosive welding [14]. However, by analyzing the compaction process with this computational method, it became clear that a melting zone is assumed to be created at a maximum temperature of 1500 K at the point of collision between the inner cylinders which means, the temperature has reached a sufficiently melting temperature.

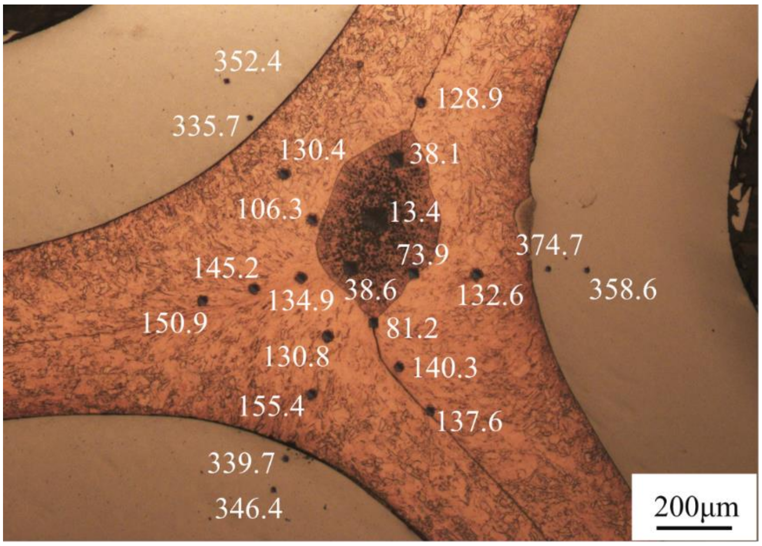

Figure 7: Results of the Vickers hardness test conducted around the melted area (sample A). Reprinted from [23].

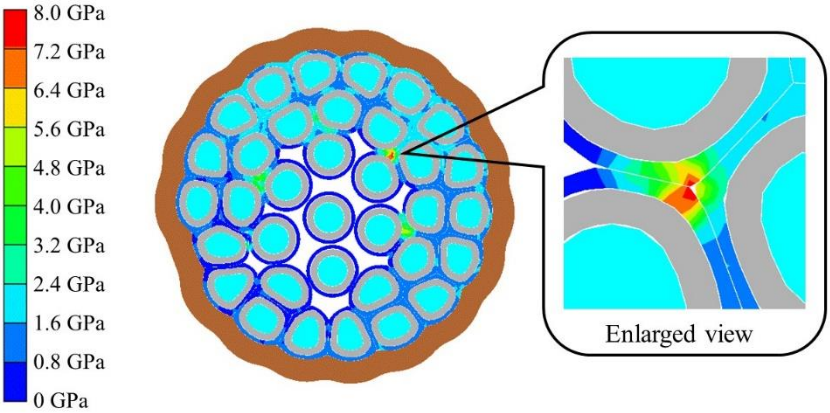

Figure 8: Pressure contour obtained by the computational simulation (sample A).

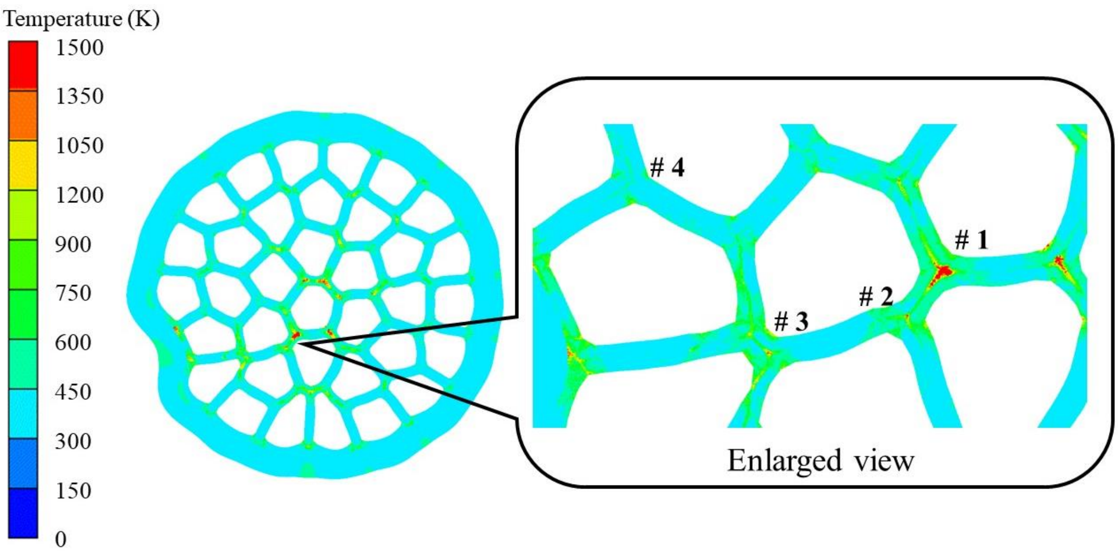

Figure 9: Temperature contour obtained by the computational simulation (sample A).

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4. RESULTS AND DISCUSSION: SAMPLE B

The experimental results for sample B are illustrated in Figure 10; here all inner pipes, with initial circular cross-sections, were formed into rectangles after explosive compression. Figure 11 illustrates the compression process, and Figure 12 presents a magnified view. A transverse optical microscope observation of sample B (paper) and the compression process based on the computational analysis reveal that the inner pipe and inner solid bar are connected without any gaps.

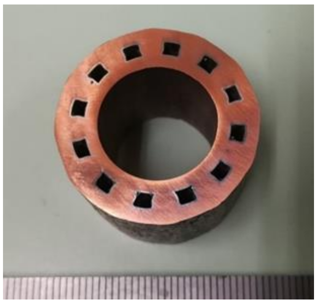

Figure 10: Cross-section of sample A viewed from the horizontal direction. Reprinted from [23] .

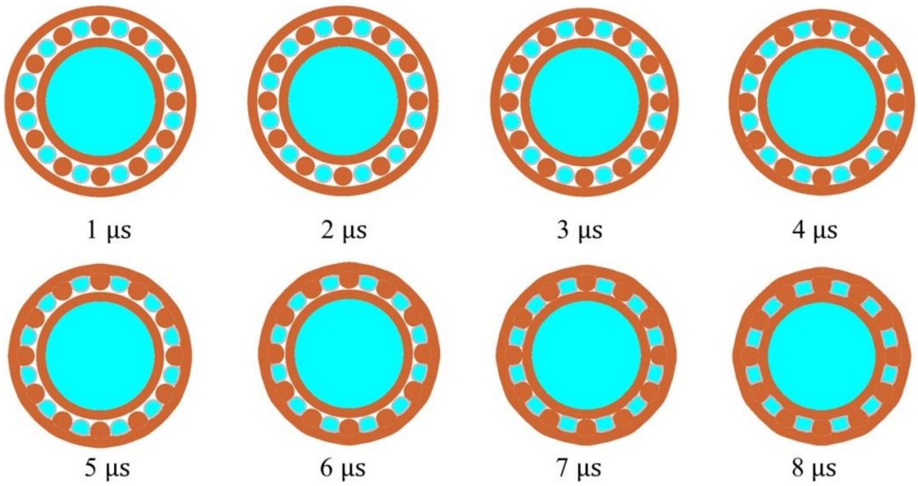

Figure 11: Analysis of the compression process.

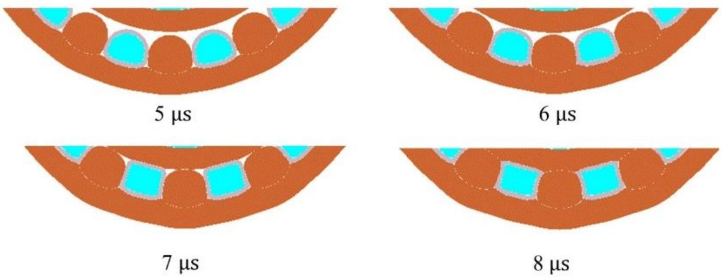

Figure 12: Compression forming process based on the computational analysis (enlarged view).

Figure 13 presents the melted portion at the triple collision point of outer pipe, inner pipe, and inner solid bars. It can be observed that the hardness of stainless-steel is significantly increased due to the work hardening induced by the plastic deformation of the material. However, the hardness values of the outer copper pipe and the inner copper bar decrease in the melted area. Figures 14 and 15 illustrate the temperature distributions during compression. Figure 14 presents a joint with the outer pipe, and Figure 15 depicts a joint with the center pipe. In both cases, the temperature exceeded the melting point, which was presumably owing to the decrease in hardness caused by the thermal effect during moulding. In particular, the area of the high-temperature part was larger on the center pipe side (Figure 15), which means the melting area was also larger. The larger melting area in the inner pipe is consistent with the experimental findings summarised in Figure 14.

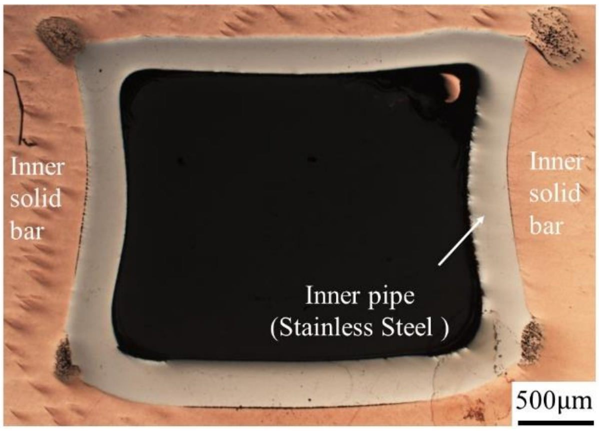

Figure 13: Transversal cross-section of sample B. Reprinted from [23].

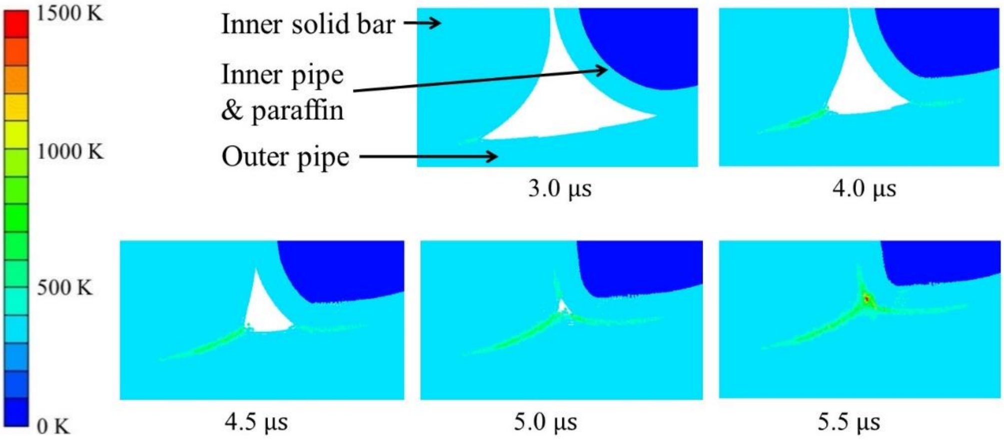

Figure 14: Compression forming process with a temperature contour obtained from the computational analysis at outer pipe side (collision point with outer pipe, inner pipe, and inner solid bar).

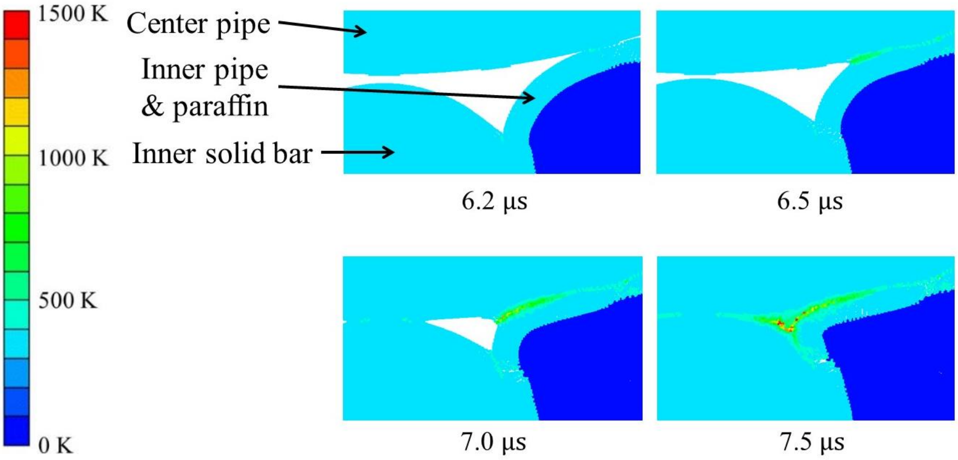

Figure 15: Compression forming process with a temperature contour obtained from the computational analysis at center pipe side (collision point with centre pipe, inner pipe, and inner solid bar).

5. CONCLUSION

In this study, we computationally analysed the fabrication process of two types of copper/stainless-steel composite UniPore structures with a stainless-steel cover layer on the entire inner surface of the copper pipe. In particular, computational analysis was used due to the difficulty in experimentally analysing the manufacturing process of such structures using the explosion crimping technique. Based on our findings, the following conclusions can be drawn:

(1) The predicted final deformed shapes corresponded well with the experimental findings. This indicates that even for a composite-type UniPore structure, the final deformed shape can be estimated using computational analysis.

(2) In some areas, the postformed cellular material presented insufficient bonding. The low impact velocity between the pipes can be attributed to the low bond strength. Therefore, to satisfy the requirements of the explosive pressure bonding conditions, a method to increase the velocity of the outer pipe must be developed.

(3) At the final stage of fabrication, the hardness of the pipes was shown to decrease significantly in some areas when the pipes collided with each other. Although this phenomenon was considered to be the collapse of metal jets in previous studies, this study has shown that the temperature at the time of collision reaches the temperature at which the metal melts.

In future studies, the fabrication conditions will be reconstructed using data obtained from the computational analysis, and a composite UniPore structure with a different base material will be investigated. This study will contribute to the clarification of the joining problem of the multi-material technique.

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Statements and Declarations:

The corresponding author states that there is no conflict of interest.

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