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Citation	Defect and Diffusion Forum. 2022, 414, p. 179-184
Version Type	AO
URL	https://hdl.handle.net/11094/100220
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Friction Stir Powder Incremental Forming for Fabrication of Sandwich-Structured Composite of Open-Cell Nickel Foam with Aluminum

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Keywords: Friction stir process, Incremental forming, Porous metal, Skin surface layer

Abstract. To fabricate sandwich-structure composite of porous metal with nonporous surface layer, the nonporous skin layer was formed on surface of open-cell type nickel foam from aluminum powder by friction stir powder incremental forming (FSPIF) process. In this process, the surface pores of the foam were filled with the powder, then the powder and the cellular matrix near the surface of the foam were incrementally hammered by a rod-shaped tool without rotation. After that, the hammered surface of the foam was incrementally stirred by the tool at a very high rotation rate. The formed skin layer was composed of two layers; the friction stirred layer (relative density: above 0.90) in the upper part and the compact layer (relative density: 0.60–0.90) in the lower part. The friction stirred layer with a maximum thickness of 0.8 mm was formed on the surface of the foam without deforming the cellular matrix of the inside of the foam under the forming conditions; a tool rotation rate of 8000 rpm, a tool feed rate of 60 mm/min, a tool pushing pitch of 0.1 mm, and a total forming depth of 5.0 mm.

Introduction

The use of porous materials has a great potential for realizing lightweight structural components due to their low density. For the more widespread use of porous materials in structural components, improvement in the strength–mass relationship is a crucial technical target because porous structures tend to be accompanied by low specific strength. One of effective solutions for the improvement is sandwich-structured composite. In the sandwich-structured composite, nonporous material layer such as thin sheet is fabricated on surface of porous material.

Some metal forming processes were applied for formation of nonporous surface layer on porous metal. Matrix metal of surface pores of a lotus-type porous copper was plastically closed and fined by wire-brushing and shot-peening processes [1, 2]. Cell walls of surface pores of a closed-cell type aluminum foam was plastically deformed and stirred by friction stir incremental forming (FSIF) process [3]. In this process, a nonporous (friction stirred) skin layer thinner than 0.4 mm was formed on the foam surface without deforming the cell walls of the inside of the foam. To form thicker skin layer, the authors developed friction stir powder incremental forming (FSPIF) process for formation of nonporous surface layer on porous metal [4]. The skin layer with a maximum thickness of 1.4 mm was formed on the surface of the closed-cell type aluminum foam.

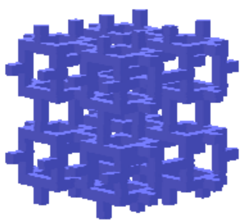
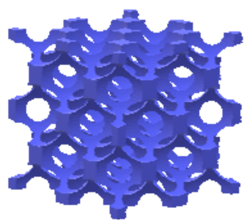
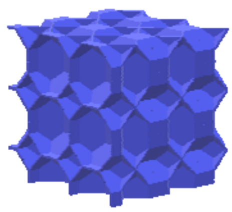
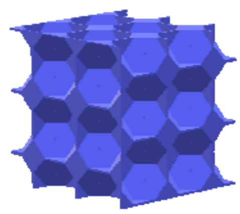
In this study, FSPIF process is applied to form skin layer from aluminum powder on the surface of open-cell nickel foam. Since strength of open-cell porous structure is generally lower than that of closed-cell porous structure, the cellular matrix of the inside of the foam is expected to be easily deformed by pressing in FSPIF process. The cellular matrix near the surface of the foam is also easily cut by tool with very high rotation rate. The formation process of the skin layer in FSPIF process is investigated by experiment using a 3-axis NC milling machine.

Comparison of compressive strength of open-cell and closed-cell foams

Finite element simulation conditions. To analyze the compressive strength of open-cell and closed-cell foams, finite element simulation was carried out by using the commercial code, Simufact Forming ver. 15.0 (MSC Software Company). Four types of the foam models shown in Table 1 were prepared. The relative density of the foam model was adjusted to 0.091–0.093. In the simulation, the elastic-plastic deformation of the cubic foam specimen in uniaxial compression was calculated. The material properties of the foam specimen was assumed to be commercially pure aluminum (JIS: A1100) in built-in database of Simufact Forming ver. 15.0.

Finite element simulation results. The calculated compressive strength ($\sigma_c/\sigma_{0.2}$, σ_c: compressive true stress at true strain of 0.05, $\sigma_{0.2}$: 0.2% proof stress) of the cubic foam specimens is shown in Table 1. The strength of the open-cell foams was 1/7–1/2 times that of the closed-cell foams. This indicates that low pushing load or short pushing stroke is required in FSPIF process of open-cell foam because the cellular matrix of the inside of the open-cell foam is easily deformed by pressing. Shear fracture of the cellular matrix also needs attention because the cellular matrix of the foam is easily shaved by rotation tool.

Table 1 Calculated compressive strength of open-cell and closed-cell foams in uniaxial compression (σ_c: compressive true stress at true strain of 0.05, $\sigma_{0.2}$: 0.2% proof stress).

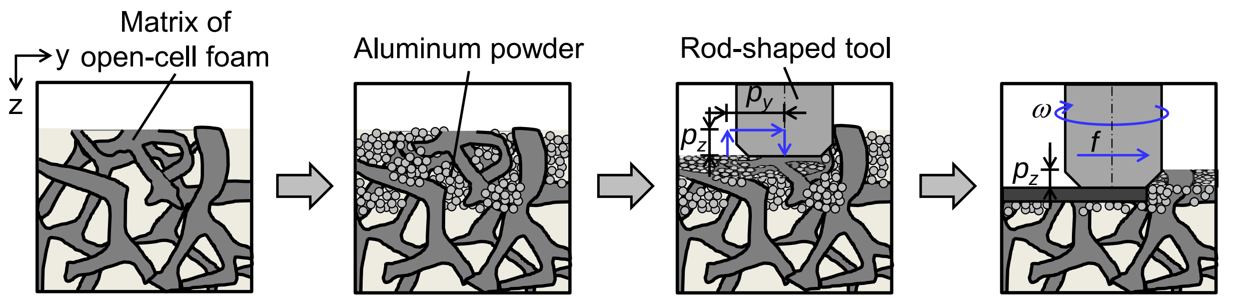
Cell type	Open		Closed	
Cell model	Gibson-Ashby [5]	Face-centered cubic [6]	Grenestedt [7]	Kelvin [8]
Appearance				
Relative density	0.093	0.091	0.093	0.091
Strength $\sigma_c/\sigma_{0.2}$	5.5×10^{-3}	3.9×10^{-3}	2.5×10^{-2}	1.1×10^{-2}

Friction stir powder incremental forming (FSPIF)

Forming procedures. Illustration of FSPIF process for open-cell foam is shown in Fig. 1. At first, powder is filled to the surface pores before start of FSPIF process. After that the powder and the cellular matrix of the foam surface are incrementally hammered by the rod-shaped tool without rotation (incremental hammering; IH), then the pressed powder and cellular matrix are incrementally stirred by the tool with high rotation rate (friction stir incremental forming; FSIF).

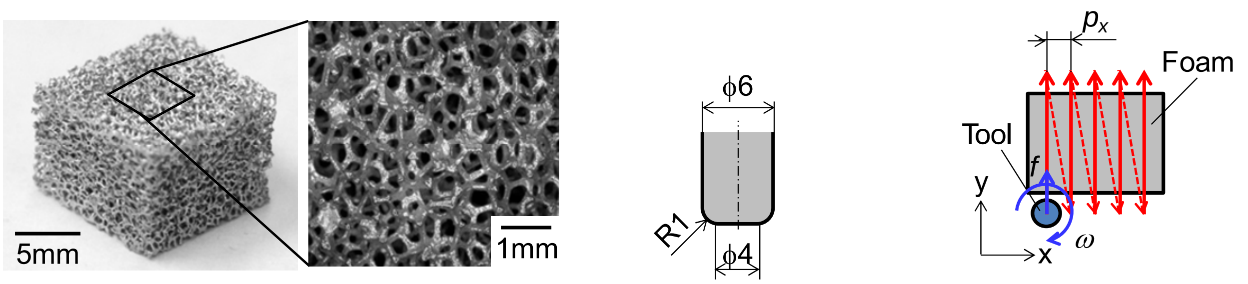
Forming conditions. A commercial open-cell nickel foam (Sumitomo Electric Industries: Celmet® [9], Ni-Cr, Fig. 2(a)) was used as a substrate of the skin layer. The mean pore diameter and relative density were 0.8 mm and less than 0.10, respectively. The foam specimen used for FSPIF process was cut as a rectangular parallelepiped with dimensions 20 mm x 20 mm x 10 mm. A commercially pure aluminum powder (Al > 99.8 mass%) was used to form the skin layer on the surface of the foam. The maximum particle diameter of the powder were about 30 μm. The powder was manually sieved and filled to the surface pores of the foam. The top surface of the filled powder was manually leveled with a wiper.

FSPIF process was performed using a 3-axis NC milling machine. The rod-shaped tool made of a high speed tool steel (JIS: SKH51, 58 HRC) was flat end shape with a corner radius of 1 mm as illustrated in Fig. 2(b). The diameter of the tool was ϕ6 mm. The tool path on the x-y plane at the *i*-th path in the z direction is illustrated in Fig. 2(c). Referring to our previous report of FSPIF process for closed-cell foam [4], the forming conditions in IH process were set as follows; the rotation rate (ω) of the tool was 0 rpm, the pushing pitch (p_z) of the tool in the z direction was 0.5 mm, the pushing rate of the tool in the z direction was 60 mm/min, the feed pitches (p_x, p_y) of the tool in the x and y directions were 0.5 mm, and the path number (n) in the z direction was four. On the other hand, the forming conditions in FSIF process were set to $\omega = 8000$ rpm, $p_x = 0.5$ mm, $p_z = 0.1$ mm and 0.5 mm, and the feed rate (f) of the tool in the y direction was 60 mm/min. The maximum total forming depth (np_z) in IH and FSIF processes were 2.0 mm and 3.0 mm, respectively.



(a) Initial. (b) Powder filling. (c) Incremental hammering (IH). (d) Friction stir incremental forming (FSIF).

Fig. 1 Illustration of friction stir powder incremental forming (FSPIF) process for open-cell foam (ω: tool rotation rate, f: tool feed rate, p_y: tool feed pitches in y direction, p_z: tool pushing pitch in z direction).



(a) Nickel foam. (b) End shape of tool. (c) Tool pass at x-y surface.

Fig. 2 Appearance of open-cell nickel foam, end shape of rod-shaped tool and tool path at *i*-th path in z direction for FSPIF process (p_x: tool feed pitches in x direction).

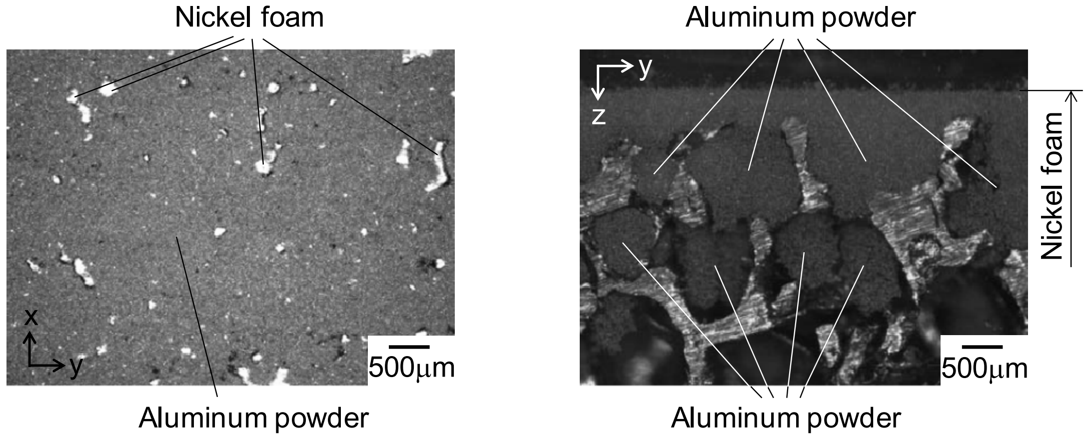
Experimental results

Powder filled to surface pore of foam. The optical microscope (OM) images of the aluminum powder supplied to the surface pores of the nickel foam is shown in Fig. 3. The pores of the foam were filled with the powder at an average depth of 1 mm from the surface of the foam. Although the pores of the foam were open cells, the pores of the foam were not filled with the powder at deeper than 1 mm from the surface of the foam due to the cohesiveness of the powder. In the experiment using aluminum powder with particle diameters of 53–106 μm, the pores of the foam were filled with the powder at deeper than 10 mm from the surface of the foam.

Formation thickness of skin layer. Fig. 4 shows the OM and the scanning electron microscope (SEM) images of the y-z cross-section of the skin layer formed with FSPIF process with $np_z = 5.0$ mm. The formed skin layer was composed of two layers in FSIF with $p_z = 0.1$ mm (Fig. 4(a)); the friction stirred layer (relative density: above 0.90) in the upper part and the compact layer (relative density:

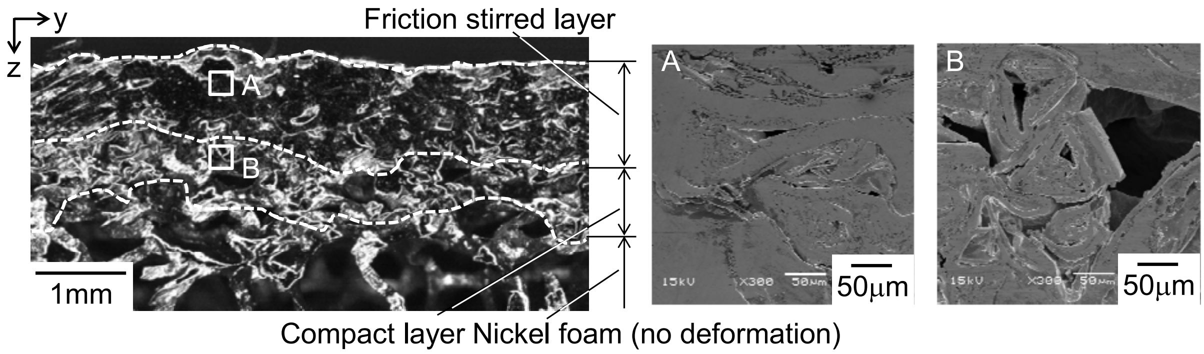
0.60–0.90) in the lower part, while the friction stirred layer was not formed in FSIF with $p_z = 0.5$ mm (Fig. 4(b)). In both cases ($p_z = 0.1$ mm and 0.5 mm), the cellular matrix below the compact layer was not plastically deformed. It is suggested that the friction stirred layer was formed by stirring of the powder and the cellular matrix by tool rotation, while the compact layer was formed by buckling and bending of the cellular matrix. The friction stirred layer is focused in this study because the strength–mass relationship of the closed-cell foam with skin surface layer were improved with increasing the thickness of the friction stirred layer in our previous reports [3, 4].

The mean formed thicknesses of the skin, friction stirred and compact layers as a function of the total forming depth (np_z) is shown in Fig. 5. The layer thickness was measured in the y-z cross-section for 1.0 mm intervals in the y direction by a digital optical microscope. The compact layer was formed during IH process ($np_z < 2.0$ mm), then the friction stirred layer was formed from the compact layer during FSIF process ($np_z > 2.0$ mm).

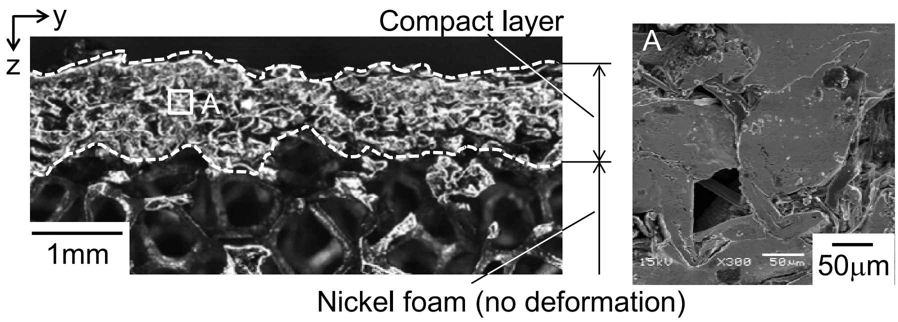


(a) x-y surface. (b) y-z cross-section.

Fig. 3 Optical microscope (OM) images of aluminum powder filled to surface pores of nickel foam.

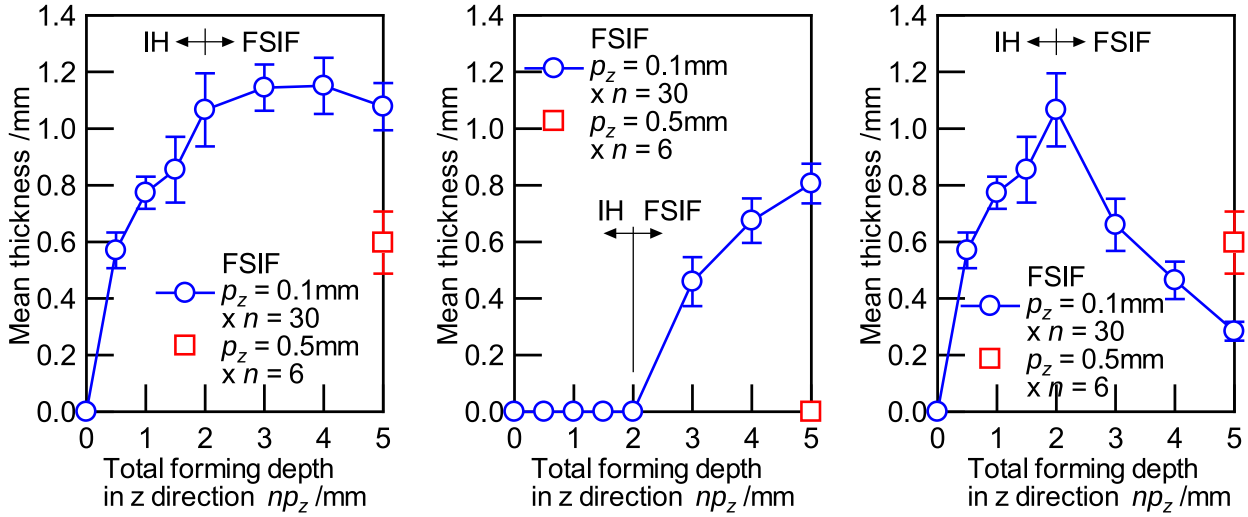


(a) $p_z = 0.1$ mm, $n = 30$ (FSIF).



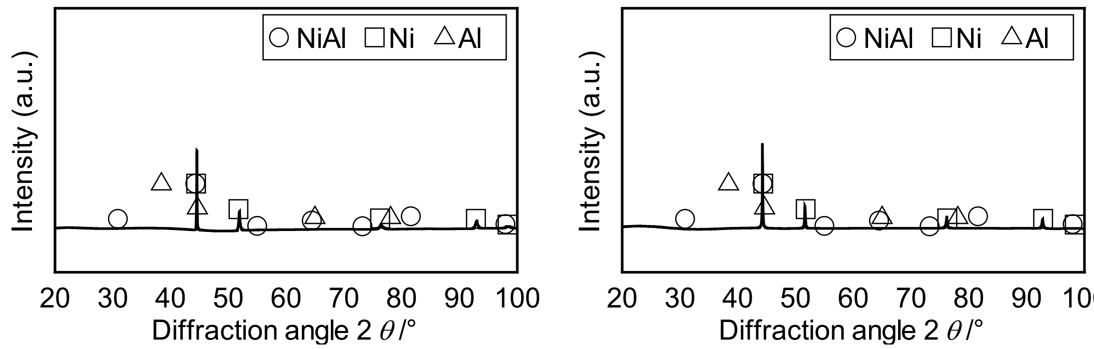
(b) $p_z = 0.5$ mm, $n = 6$ (FSIF).

Fig. 4 Optical microscope (OM) and scanning electron microscope (SEM) images of y-z cross-section of skin layer in FSPIF process with $np_z = 5.0$ mm (IH: 2.0 mm).



(a) Skin layer. (b) Friction stirred layer. (c) Compact layer.

Fig. 5 Mean thicknesses of formation layers on surface of nickel foam in FSPIF process.



(a) Friction stir layer. (b) Compact layer.

Fig. 6 X-ray diffraction pattern from y-z cross-section of skin layer formed from nickel foam and aluminum powder in FSPIF process with np_z = 5.0 mm.

Compositions of skin layer. Fig. 6 shows the x-ray diffraction pattern from the y-z cross-section of the skin layer formed with FSPIF process. In the friction stirred and compact layers, aluminum and nickel were in a mixture state, however the intermetallic compound was not detected. The intermetallic compound may be formed by further stirring by tool rotation in FSPIF process and heat treatment after FSPIF process.

Summary

In this study, FSPIF process was applied to form skin layer from aluminum powder on the surface of open-cell nickel foam. The formation mechanism of the skin layer from the powder was investigated. The following remarks are obtained.

1) In comparison between open-cell and closed cell foams with same relative density, the strength of the open-cell foams was 1/7–1/2 times that of the closed-cell foams. It was suggested that low pushing load or short pushing stroke was required in FSPIF process of open-cell foam.
2) The compact layer (relative density: 0.60–0.90) was formed during IH process, then the friction stirred layer (relative density: above 0.90) was formed from the compact layer during FSIF process.
3) The friction stirred layer with a maximum thickness of 0.8 mm was formed on the foam surface without deforming the cellular matrix of the inside of the foam under FSPIF conditions; a tool

rotation rate of 8000 rpm, a tool feed rate of 60 mm/min, a tool pushing pitch of 0.1 mm, and a total forming depth of 5.0 mm.

Acknowledgement

This study was financially supported in part by the Light Metal Educational Foundation, Inc.

References

[1] J. Lobos, S. Suzuki, H. Nakajima, Y.S. Ji, H. Fujii, D. Terada, N. Tsuji, Structural change and improvement of the mechanical properties of a lotus-type porous copper by wire-brushing, Journal of Physics: Conference Series, 165 (2009) 012070.

[2] S. Koriyama, S.A. Paiboon, S. Suzuki, M. Asakawa, T. Ide, H. Nakajima, Enhancement of the hardness of lotus-type porous copper by shot peening, Steel Research International, Special Edition (2012) 1215-1218.

[3] R. Matsumoto, H. Tsuruoka, M. Otsu, H. Utsunomiya, Fabrication of skin layer on aluminum foam surface by friction stir incremental forming and its mechanical properties, Journal of Materials Processing Technology, 218 (2015) 23-31.

[4] R. Matsumoto, S. Mori, M. Otsu, H. Utsunomiya, Formation of skin surface layer on aluminum foam by friction stir powder incremental forming, International Journal of Advanced Manufacturing Technology, 99-5-8 (2018) 1853-1861.

[5] L.J. Gibson, M.F. Ashby, M.F., Cellular solids – structure and properties, Cambridge University Press, 1997, 183-217.

[6] W. Pabst, T. Uhlířová, E. Gregorová, A. Wiegmann, Young's modulus and thermal conductivity of model materials with convex or concave pores – from analytical predictions to numerical results, Journal of the Europian Ceramic Society, 38-7 (2018) 2694-2707.

[7] B.-Y. Su, C.-M. Huang, H. Sheng, W.-Y. Jang, The effect of cell-size dispersity on the mechanical properties of closed-cell aluminum foam, Matrials Characterization, 135 (2018) 203-213.

[8] W. Pabst, T. Uhlířová, E. Gregorová, A. Wiegmann, Young's modulus and thermal conductivity of closed-cell, open-cell and inverse ceramic foams – model-based predictions, cross-property predictions and numerical calculations, Journal of the Europian Ceramic Society, 38-6 (2018) 2570-2578.

[9] S. Inazawa, A. Hosoe, M. Majima, K. Nitta, Novel plating technology for metallic foam, Sumitomo Electric Industries (SEI) Technical Review, 71 (2010), 23-30.