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Fabrication of skin layer on aluminum foam surface by friction stir incremental forming and its mechanical properties

Ryo Matsumoto[a,*], Hiroyuki Tsuruoka[a], Masaaki Otsu[b], Hiroshi Utsunomiya[a]

[a] *Division of Materials and Manufacturing Science, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita 565-0871, Japan*
[b] *Department of Mechanical Engineering, Faculty of Engineering, University of Fukui, 3-9-1 Bunkyo, Fukui 910-8507, Japan*

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ABSTRACT

Porous metals with a nonporous skin surface layer (sandwich structure) have a potential to improve their mechanical properties. Friction stir incremental forming process for sheet metals is applied to form the surface of a closed-cell type aluminum foam. In this process, the cell walls near the aluminum foam surface are plastically deformed and stirred by the rotation of a forming tool at a very high rate, and the nonporous skin layer is fabricated on the surface of the aluminum foam. Nonporous aluminum skin layer with a thickness less than 400 μm is fabricated at the surface without internal fracture of the aluminum foam under the following forming conditions; a tool rotation rate of 8000 rpm, a tool feed rate of 60 mm/min, and a total forming depth of 7 mm. To investigate the mechanism of formation of the skin layer, the skin layers fabricated with friction stir incremental forming and incremental hammering are compared. The compressive deformation behavior of aluminum foam with a skin surface layer is investigated by performing uniaxial compression test. The specific compressive strength of aluminum foam with a nonporous skin surface layer is improved by approximately 20–50%.

1. Introduction

Lightweight structural components are in demand in automotive industries because of environmental concerns (Kleiner et al., 2003). Since porous metals contain many pores, their density is much lower than that of nonporous metals. Owing to this, porous metals are attractive materials for weight reduction of the structural components. Banhart (2001) and Ashby et al. (2000) have previously discussed the manufacture, characterization and application of porous metals have previously been discussed. Their porous structures are not only light in weight but also have some unique characteristics such as high energy absorbing capacity, high sound absorbing capacity and low thermal properties.

Various methods for the fabrication of porous metals have been developed. For example, Baumgärtner et al. (2000) have developed the precursor method and Miyoshi et al. (2000) have developed the casting process of molten aluminum and stabilizing bubbles for the fabrication of aluminum foam. Such porous metals must have the required characteristics if they are to be used widely in industrial products. In particular, the strength–mass relation of porous metals should be improved because the use of porous metals in structural components tends to reduce their strength as well as their mass. The control of the pore distributions of porous metals is crucial to the production of structural components with the desired characteristics, such as functionally graded properties and an enhanced strength–mass relation. In a case of forming of honeycomb sandwich panels, porous metals with a thin nonporous skin surface layer have attractive features, such as enhanced strength, an extension of the plateau region in compression (Banhart and Baumeister, 1998), a reduction in the notch effect, and simplified joining with other components. As surface treatments for enhancing the strength–mass relations of porous metals, Seeliger (2002) has suggested the fabrication of an aluminum foam sandwich (AFS) component and Kitazono et al. (2009) have suggested the fabrication of an aluminum foam coated with resin. Alternately, metal forming processes have been used to fabricate skin layers on porous metal surfaces. For example, Lobos et al. (2009) and Koriyama et al. (2012) have applied wire-brushing and shot peening processes to form the surfaces of lotus-type porous copper for the purpose of improving their mechanical properties, respectively. In these processes, the cell walls near the surface were plastically deformed, and a nonporous skin layer with fine grains was fabricated at the surface.

In this study, in order to enhance the strength–mass relation of a closed-cell type aluminum foam, friction stir incremental forming (FSIF) process for sheet metals (Otsu et al., 2009) is implemented

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[*] Corresponding author. Tel.: +81 6 6879 7500; fax: +81 6 6879 7500.
E-mail address: ryo@mat.eng.osaka-u.ac.jp (R. Matsumoto).

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to form the surface of the aluminum foam. The mechanism of formation of the skin layer on the aluminum foam surface is discussed by comparing the skin layers fabricated with FSIF and incremental hammering (IH). The compressive behavior of the fabricated aluminum foam with a skin surface layer is investigated with uniaxial compression testing.

2. Friction stir incremental forming for porous metal surfaces

Friction stir incremental forming process which was originally developed as novel incremental sheet metal forming method (Otsu et al., 2009) was employed in this study to fabricate nonporous skin layers on porous metal surfaces. This process combines single point incremental sheet forming with friction stir welding. A bar-shaped tool with a flat end surface with a rotation rate of 1000–10,000 rpm is pushed against the sheet metal. The sheet metal is locally deformed by the rotation and movement of the tool. In this process, the sheets are heated and introduced severe plastic deformation involving dynamic recrystallization and grain refinement that arises as a result of the friction produced by the rotation of a forming tool at a very high speed. Similar forming processes can be used in the fabrication and forming of the aluminum foam. Hangai and Utsunomiya (2009) fabricated aluminum foam from aluminum and TiH_2 powders by performing friction stir processing (FSP). Kwon et al. (2008) modified the surface structures of aluminum foam by the friction surface modification (FSM) process. Local heating of the aluminum powder and the deformation of the aluminum foam were caused by the rotation of the tool in these forming processes, but the fabrication with these approaches of nonporous skin surface layers on porous metal surfaces has not previously been reported.

The porous metal used in this study was a commercial closed-cell type aluminum foam: ALPORAS (Shinko Wire Company, Ltd., Fig. 1) (Miyoshi et al., 2000). The ALPORAS was produced by adding calcium to increase viscosity and titanium hydride powder as a foaming agent of molten aluminum, which was mixed in a casting chamber. The foamed melt was then cooled to form solid foam. The mean relative density of the ALPORAS was $\rho = 0.1$ (mean porosity: 0.9), and the true density was assumed to be 2.7 Mg/m^3 (pure aluminum). The mean pore diameter was ϕ4 mm, however, the scatters of the size and shape of the pores in the aluminum foam were large, as shown in Fig. 1. The ALPORAS specimen had a rectangular parallelepiped with the dimensions 30 mm × 22 mm × 24 mm.

Table 1
Friction stir incremental forming (FSIF) conditions for aluminum foam.

Tool rotation rate ω (rpm)	400–15,000
Tool feed rate f (mm/min)	20–2000
Moving pitch of tool in z direction p_z (mm)	0.5
Moving pitch of tool in x direction p_x (mm)	0.5
Total pass number of forming in z direction n	1–20
Total forming depth in z direction np_z (mm)	0.5–10

The friction stir incremental forming process for porous metals is illustrated in Fig. 2. Forming was carried out on a 3-axis NC milling machine. A bar-shaped tool with a flat end and a diameter of ϕ6 mm (diameter at end surface: ϕ4 mm) was made of high speed tool steel (JIS: SKH51, 58 HRC). The diameter at the end surface of the tool was the same as the mean pore diameter of the aluminum foam. The surface roughness at the end surface of the tool was $R_a < 1.6\,\mu$m. The tool was pushed against the surface of the aluminum foam with a rotation rate of $\omega = 400$–$15{,}000$ rpm in the z direction with $p_z = 0.5$ mm under dry condition (without lubrication). The tool pass is shown in Fig. 2(c) in the x–y plane at the i-th pass number in the z direction. The tool was moved with a feed rate of $f = 20$–2000 mm/min in the y direction and a pitch of $p_x = 0.5$ mm. The pass number in the z direction was $n = 1$–20 (total forming depth $np_z = 0.5$–10 mm). The forming conditions are summarized in Table 1.

3. Experimental results

3.1. Effects of varying pass number in z direction

Fig. 3 shows photographs of the initial and formed aluminum foams. The surface of the aluminum foam was plastically deformed and stirred by the rotating tool, and the cell walls near the surface

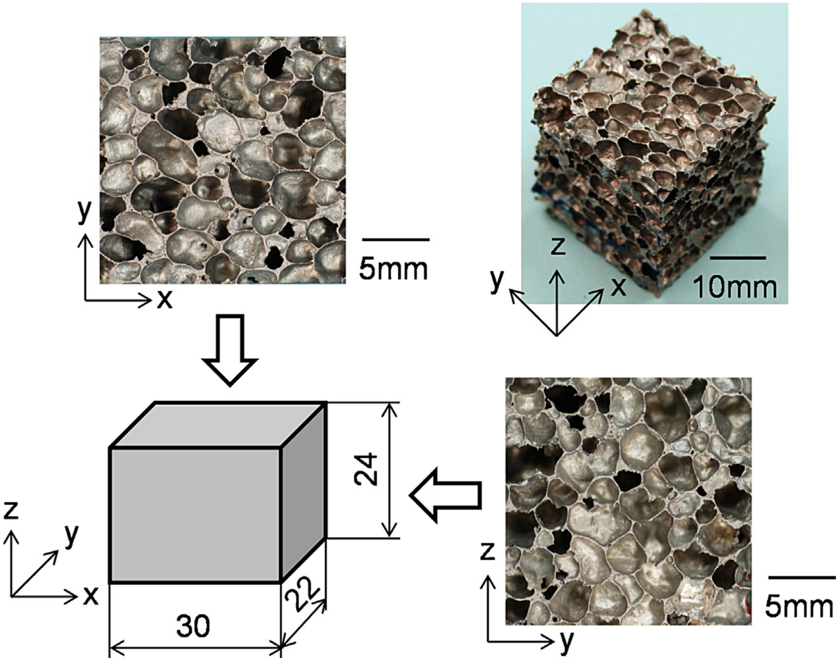

Fig. 1. Initial shape and appearance of ALPORAS specimen (mean relative density ρ: 0.1, mean pore diameter: ϕ4 mm).