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Filling of surface pores of aluminum foam with polyamide by selective laser melting for improvement in mechanical properties

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ABSTRACT

To improve mechanical properties of porous structured materials, selective laser melting (SLM) was used to fill the surface pores of a commercial closed-cell type aluminum foam with polyamide 12 (nylon 12). It was found that polyamide powder was continuously melted and solidified under laser irradiation at an average energy density of 10 J/mm^2. The mechanical properties of the aluminum foam with fabricated polyamide surface layer (composite sandwich structure) was investigated using a uniaxial compression test. The specific compressive strength of the foam with surface layer increased 2.5 times in maximum higher than that of the foam without surface layer. The improvement was not only due to the high specific strength of the polyamide but also due to the formation of the sandwich structure.

1. Introduction

Porous metals are one of attractive materials for lightweight structural components due to their low density. Ashby et al. (2000) and Banhart (2001) have discussed the manufacture, characterization, properties, and application of porous metals. The structures of porous metals exhibit not only light in weight but also some unique functional characteristics, such as a low coefficient of heat transfer (Lu et al., 1998) and a high sound absorbing capacity (Lu et al., 1999). However, in general, the low density is the most significant feature of porous metals. The widespread use of porous metals in industrial products requires further improvements in their mechanical properties, especially in the strength-mass relationship because the low mass of porous metals tends to be accompanied by a relatively low strength due to coarse microstructure by heat treatment at high temperature.

In order to improve the mechanical properties without losing low density characteristic, several methods were reported. Mondal et al. (2009) considered to improve the strength-mass relationship by strengthening the metal matrix. Hangai et al. (2013), and Jeenager and Pancholi (2014) considered to achieve a gradation of functional properties by controlling the pore size, shape, and distribution. Sandwich structures formed by laminating with a thin sheet can also provide an effective approach to improve the mechanical properties of the structural components. Some fabrication methods to form sandwich structures have been considered for porous metals. Seeliger (2002) joined aluminum foam sandwich (AFS) to nonporous metal sheets. Kitazono et al. (2009) and Yuan et al. (2015) coated a resin on aluminum foam. Nonporous skin layers over the surface of a porous metal could be fabricated by plastic deformation of the cell walls near the surface of the porous metal. For example, Lobos et al. (2009) and Matsuda et al. (2013) applied wire-brushing and shot-peening processes to close pores on the surface of a lotus-type porous copper, respectively. Matsumoto et al. (2015b) reported friction stir incremental forming (FSIF) process was applied to deform the surface of a commercial closed-cell type aluminum foam. The strength-mass relationship of the aluminum foam was improved by 1.2–1.5 times by formation of nonporous skin surface layer by FSIF process. However, the bulk volume fraction of the nonporous skin surface layer formed by FSIF process was considerably small. If thick nonporous skin surface layer is required, more pores near the surface of the aluminum foam is needed to be closed by FSIF process. Since manufacturing cost of porous metals is generally high, the consumption of the aluminum foam with large volume is one of disadvantages of the application of FSIF process on the aluminum foam.

In one of manufacturing processes with increasing volume incrementally during the process, additive manufacturing (AM) is

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an innovative manufacturing process for rapid production of three-dimensional product prototypes (Kruth (1991) and Kruth et al. (2007)). Yadroitsev et al. (2009) applied AM processes to produce porous structures and Sun et al. (2013) tested mechanical properties of porous structure produced by AM process. In fabrication of porous structures by AM processes, the pore size, shape, and distribution are easily controlled, however, the strength of the fabricated porous metals tends to be lower than that of conventional porous metals because these materials are fabricated by melting of metal powder and solidification. To improve the strength of porous metals fabricated by AM processes, some research works are recently progressed. Challis et al. (2014) developed open-cell structures of Ti-6Al-V titanium alloy designed using topology optimization to realize high specific strength and stiffness in selective laser melting (SLM), one of AM processes. Liu et al. (2015) and Liu et al. (2016) optimized manufacturing parameters for open-cell structures of Ti-24Nb-4Zr-8Sn biomedical titanium alloy in SLM and electron beam melting (EBM), respectively. Attar et al. (2014) reported mechanical properties of Ti-TiB composites fabricated by SLM was the same level with cast one.

In above recent research works, the strength of porous metals fabricated by AM processes is gradually improved, however, the fabrication size of the porous metals is still limited, and the production time tends to be long in AM processes. For these reasons, AM processes were considered to be partly applied only to the surfaces of conventional porous metals. For fabrication of porous metals with nonporous surface layer, Kanatani et al. (2014) applied SLM to fill the surface pores of a commercial closed-cell type aluminum foam with aluminum powder. The powder was melted and solidified by SLM. Matsumoto et al. (2015a) subsequently investigated the strength-mass relationship of the aluminum foam with the fabricated nonporous aluminum surface layers. Although this approach was prevented from decreasing the bulk volume of the aluminum foam during the fabrication of the nonporous surface layer, the strength-mass relationship was not improved sufficiently because the aluminum powder was not sufficiently melted and solidified under laser irradiation of SLM. Furthermore, the fabrication of a surface layer of a dissimilar material with high strength (a composite sandwich structure) was mentioned to be effective in improving the strength-mass relationship.

In this study, in order to improve the strength-mass relationship i.e., specific strength of an aluminum foam with a nonporous surface layer, the surface pores of the aluminum foam were considered to be filled with a dissimilar material with high strength by SLM. Polyamide was used as the dissimilar material. The nonporous surface layer of the polyamide was fabricated via SLM. The laser irradiation conditions were optimized for the fabrication of the nonporous polyamide surface layer on the surface of a commercial closed-cell type aluminum foam. The deformation behavior and the mechanical properties of the aluminum foam fabricated with the polyamide surface layer were investigated using a uniaxial compression test. The bonding state at the polyamide-aluminum foam interface and the strength-mass relationship were discussed.

2. Experimental procedures

2.1. Aluminum foam and polyamide powder

A commercial closed-cell type aluminum foam (Shinko Wire Company, Ltd.: ALPORAS, Al-Ca-Ti (Miyoshi et al., 2000; Fig. 1(a)) was used. The ALPORAS was produced by mixing the molten aluminum, titanium hydride powder, which acted as a blowing agent, and calcium powder, which increased the viscosity, in a casting chamber. The foamed melt was then cooled to form a solid foam. The mean relative density and the mean pore diameter of the foam were 0.1 (mean porosity: 0.9) and ϕ4 mm, respectively. However, the pore sizes and shapes in the foam were widely distributed statistically, as shown in Fig. 1(a). The true density of the matrix of the foam was assumed to be the same as that of pure aluminum, 2.70 Mg/m^3. Initial bulk density was ρ_0 = 0.27 Mg/m^3. The foam specimens used in the subsequent SLM was cut using a wire electrical discharge machining (EDM).

A commercial polyamide 12 (PA12, nylon 12) powder (Fig. 1(b)), which is commonly used for SLM, was used to fill the surface pores of the aluminum foam. The mean particle diameter was about 10 μm. The density and melting point of the powder were 1.02 Mg/m^3 and 449 K, respectively.

2.2. Selective laser melting (SLM) conditions

Fig. 2 shows photograph and schematic illustrations of the experimental apparatus used for SLM. A continuous Nd:YAG laser (Miyachi Corporation: ML-7062A) with an average power of 30 W was used for laser irradiation to the polyamide powder and the aluminum foam surface. Laser scanning on the x-y plane was controlled by angles of a galvanometer mirror, while the vertical position (z) of the stage in the chamber was manually adjusted by a jack. The foam specimen was heated to a temperature of 413 K using a heater under the specimen. After manually supplying the powder with a thickness of 0.4 mm (2 mg/mm^2) to the surface pores of the foam using a sieve, the relative density of the supplied powder bed was 0.54. The laser beam was then irradiated to the bed at an average power of P_{avg} = 30 W, a spot diameter of d_s = 0.1–0.6 mm, a scan speed of v_s = 1–10 mm/s in the y direction, and a hatching pitch of 0.1 mm in the x direction under an air atmosphere. The average energy density of the laser beam was set to $E_{avg} = P_{avg}/(d_s \cdot v_s)$ = 5–300 J/mm^2 by controlling d_s and v_s. After the laser irradiation of one layer across the x-y plane, the stage was lowered vertically by 0.4 mm in the z direction, and a fresh powder was manually supplied to a thickness of 0.4 mm on top of the previously laser-irradiated surface using a sieve. The laser scanning operations across the x-y plane and the stage movement along the z direction were conducted repeatedly. The laser scanning across the x-y plane in the x and y directions was alternately changed for x and y directions by layer-by-layer, as illustrated in Fig. 2(c). The laser irradiation conditions (P_{avg}, d_s, v_s) and the supplied thickness of the applied powder bed were determined from SLM conditions of aluminum powder in our previous research work (Kanatani et al., 2014).

2.3. Uniaxial compression conditions

The mechanical properties of the aluminum foam with the polyamide surface layer (composite sandwich structure) were measured by uniaxial compression test using a material testing machine. Three types of specimens were examined: aluminum foam specimen without a skin surface (as-received aluminum foam), monolithic polyamide specimen fabricated via SLM, and aluminum foam specimen with four lateral polyamide surface layers fabricated via SLM.

Fig. 3 shows photographs of the specimens for the uniaxial compression test. The aluminum foam specimen with and without the polyamide surface layer were cubic in shape with dimensions of 25 mm × 25 mm × 25 mm (including the polyamide surface layers), while the monolithic polyamide specimen was cubic in shape with dimensions of 10 mm × 10 mm × 10 mm. The polyamide surface layers were fabricated via SLM on the lateral four surfaces of the aluminum foam specimen. The monolithic polyamide specimen was fabricated from the powder via SLM under the identical conditions used to fabricate the polyamide surface layers of the aluminum foam specimen. The initial relative densities of the polyamide spec-