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Effect of track spacing on porosity of metallic foam fabricated by laser melting deposition of Ti6Al4V/TiH_2 powder mixture

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ABSTRACT

We fabricated porous metallic materials using laser melting deposition, wherein a mixture of a metal powder and a foaming agent is sprayed while a high-energy laser is irradiated on it to melt and deposit it, resulting in foaming action. To fabricate the porous materials, we used a powder of Ti6Al4V alloy. TiH_2, a foaming agent, was employed to create pores within the deposited material. The track spacing was varied to examine its effect on the foaming characteristics and the porosity and pore size and distribution of the deposited material. We also investigated the effects of representative process parameters, including the laser power, foaming agent content, and powder feed rate. The results showed that, when the track spacing was smaller than the width of the deposited beads, pores were generated by the foaming agent. In the opposite case, however, open-cell pores were created between the tracks. This was because the fluidity of the molten metal varied with the track spacing, confirming that the porosity can be adjusted by changing the track spacing. Moreover, as the laser power was decreased or the powder feed rate increased, the porosity increased. Hence, the porosity is related to the cooling rate of the molten metal.

1. Introduction

Among the various lightweight materials being explored, porous materials are of particular interest, owing to their unique properties. These materials contain numerous pores, and their physical properties include lightweightness, sound insulation/absorption, shock absorption, high compression performance, and electromagnetic shielding. Further, they are ultralight but maintain their metallic properties and show good machinability [1–4]. Because of these advantages, porous materials are used widely in the automobile, aircraft, shipbuilding, train, construction, and biomedical industries as well as in power plants and batteries.

Foaming is the most common way of fabricating porous materials. In particular, titanium metal foam, which is used in many areas, has emerged as a topic of intensive research interest. Because titanium is lightweight and shows high strength and corrosion resistance, it is used in many areas, including aerospace, marine, and automobile parts. Titanium does not induce allergic reactions and is thus suitable for making implants and artificial bone [5]. Because titanium has a high melting point, titanium metal foam has traditionally been fabricated by the space holder technique [6], melt gas injection, or sintering with a foaming agent [7].

Recently, researchers are paying attention to the fabrication of porous structures using additive manufacturing techniques suitable for the production of small batches. Additive manufacturing is the process of making three-dimensional objects by using concentrated heat energy to melt metal powders and solidifying and depositing materials in a layer-by-layer manner [8]. Moreover, additive methods can be used to fabricate large objects and can also be used to produce objects of various shapes. Further, even microscopic parts are being produced with high precision by additive manufacturing techniques [9].

In contrast to the conventional foaming techniques, additive manufacturing techniques can produce porous materials in any shape. Further, they allow for control over the size, density, and distribution of pores in any area of interest. While laser-assisted metal deposition for forming porous materials is still in the development stage, there have been significant advances in three-dimensional (3D) printing systems as well as the software programs needed to run these systems. Thus, this study aimed to extend the applicability of additive manufacturing to lightweight and multifunctional materials.

Kathuria was the first to use a Nd-YAG laser and TiH_2, which is a foaming agent, on an Al substrate to fabricate metal foams. He aimed to determine the optimal foaming conditions by varying the laser power, velocity, and duty cycle. A porous structure consisting of a closed cell

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structure with a relative density of 0.33–0.39 and porosity of 61–67% could be formed ultimately [10]. Pape et al. performed a foaming experiment using a laser and mixtures of Ti powder and $CaCO_3$, $MgCO_3$, or $MgTiO_3$, which are foaming agents. It was observed that the content of the foaming agent affected the pore size. Further, the use of a mixture consisting of the metal powder and multiple foaming agents resulted in foams with a higher porosity than was the case when a single foaming agent was employed [11].

The fabrication of open-cell structures using PBF has been studied by several researchers [12–14]. In this process, the powder is placed in a thin layer to form a base material. Next, a laser is selectively irradiated onto the layer to melt and deposit the material. Xue et al. fabricated porous titanium structures with a porosity of 17–58% and pore sizes of up to 800 μm by using the laser engineering net shaping technique with Ti powder and adjusting the laser power, powder feed rate, and laser scan rate. The porosity and pore size increased with a decrease in the laser power, increase in the powder feed rate, and increase in the laser scan rate [12]. Stamp et al. used the selective laser melting (SLM) beam overlap technique to fabricate an aggregate material from grade 1 cp-Ti with an average pore size of 440 μm and porosity of 71%. This result indicates that the SLM beam overlap technique is a very promising way of fabricating functional aggregate materials [13]. Xiang et al. fabricated porous implants with a porosity of 60.1% from Ti6Al4V by using the electron beam melting (EBM) process, which is a direct metal deposition technique. They reported that, by using the EBM process, they could accurately control the internal porous structure of the implants. Subsequent cell culture experiments performed in test tubes indicated that osteoblasts multiplied and spread within the implants owing to the porous structure [14].

Other research groups have fabricated porous structures by varying the track spacing while using a metal 3D printer and a high-energy heat source [15]. When fabricating a porous material by adjusting the track spacing, a foaming agent is not needed. Ahsan et al. mixed gas-atomized Ti6Al4V powder with 316 L stainless steel powder and varied the laser track spacing during laser direct metal deposition (LDMD). Using this method, they were able to fabricate a porous metal with porosity of 25%. Further, they reported that increasing the overlap ratio increased the porosity [16]. Parthasarathy et al. fabricated porous metals from Ti6Al4V using the EBM method while varying the thickness and spacing of the tracks. They reported that they quickly produce customized implants with fully connected pores, with the porosity of the implants being 49.75–70.32% [17].

As suggested by the above-mentioned studies, additive manufacturing techniques for fabricating porous materials are mostly limited to open-cell structures, as it is impossible to use a foaming agent to create closed-cell pores in the PBF process. Meanwhile, the fabrication of metal foam with a closed-cell structure by the DED method has not been reported yet. In our previous research [18], for the first time, we attempted to fabricate carbon steel foams by the DED method from a mixture of carbon steel P21 powder and foaming agent ZrH2. Based on this work, metal foams with a closed-cell pore structure could be fabricated. In this study, we attempted to fabricate titanium foams containing both open-cell pores and closed-cell pores by using the DED technique. Closed-cell voids were created using the foaming agent TiH2 (which is more effective for titanium), while track spacing was simultaneously varied to generate voids corresponding to an open-cell structure. In other words, we both used a foaming agent and varied the track spacing to create pores. Ti6Al4V powder was mixed with the foaming agent TiH_2, and the mixture was deposited in a layer-by-layer manner. A preliminary survey was performed to identify the determining process parameters, including the track spacing, laser power, and foaming agent content. The deposition characteristics, sample porosity, and pore size and distribution for different process parameters were investigated.

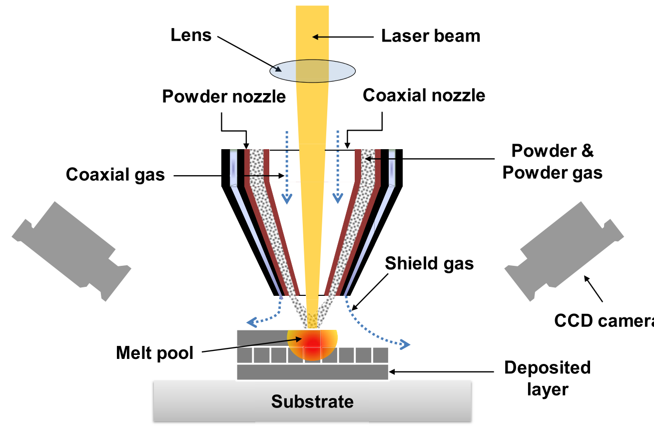

Fig. 1. Principle of DED process.

2. Materials and methods

2.1. Direct energy deposition

The laser-assisted metal deposition system used in this study, namely, a direct metal tooling MX3 device developed by Insstek Co., Ltd. (South Korea), is shown in Fig. 1. The device consists of a 4-kW CO_2 laser, which serves as the heat source, a numerical control (NC) system (including an industrial operating computer), MX-CAM software, a five-axis NC machine tool, and a powder feeding system consisting of three hoppers and a coaxial powder nozzle. The beam spot diameter is 1.0 mm, and the beam exhibits a top-hat intensity distribution. The experiments were performed using argon as the shielding gas in order to protect the workpiece against oxidation as well as the carrier gas for the injected powder. The processing head, equipped with a coaxial powder supply, was integrated with the optical system so that the powder could be fed coaxially with the laser beam on the substrate surface, which was placed 9 mm from the nozzle tip.

2.2. Materials used

Ti6Al4V (Grade 5) was used as the base metal in this study. It shows excellent corrosion resistance, can be thermally treated, and thus is a widely used Ti alloy [19]. The metal powder (of the same material as the base metal) used for the deposition process consisted of spherical particles with a diameter of 50–140 μm. It was fabricated by melting Ti6Al4V alloy and subjecting the melt to gas atomization. The foaming agent used was TiH_2, which is a metal alloy consisting of titanium and hydrogen. TiH_2 is also used widely as a foaming agent [20,21]. The size of the TiH_2 powder particles was 53–75 μm. Table 1 shows the chemical compositions of the base metal and metal powder. The Ti6Al4V powder was mixed with the TiH_2 powder in a ratio of 5:5 and 7:3 for approximately 1 h in a mixer. A base metal sample with the dimensions of 100 mm × 50 mm × 5 mm was prepared and cleaned with ethanol before the experiment.

2.3. Process conditions

The primary process parameter during the DED-based fabrication of porous materials is the track spacing (TS). This study aimed to examine the effect of this parameter on the foaming and deposition characteristics by focusing on the height of the deposited material as well as the number and size of the pores generated under each set of conditions. In addition, the effects of the foaming agent ratio (FR), power (P), and powder feed rate (PF) were also evaluated. These parameters affect the energy density and powder density, which determine the powder melting process during deposition. In a preliminary experiment, the following conditions were determined to be suitable for forming pores