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COMPRESSIVE PROPERTIES OF POROUS ALUMINUM ALLOYS HAVING ORDERED AND DISORDERED CELL STRUCTURES

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ABSTRACT

Impact energy absorbing system for automotive is an important technology. Open-cell porous aluminum alloys were manufactured through Powder Bed Fusion (PBF) process. Compressive properties of the porous aluminum alloy depend on the cell structure as well as the porosity. The authors manufactured two ordered cell structures, truncated octahedron and rhombic dodecahedron, and one disordered cell structure, random Voronoi structure using a 3D-CAD software. Compression tests revealed the anisotropic deformation of the porous aluminum alloy with ordered cell structure. On the other hand, the porous aluminum alloy with disordered cell structure showed relatively isotropic and uniform deformation, which is suitable for energy absorbing applications. Therefore, controlling the disordered cell structure designed by Voronoi diagram enables to develop the advanced porous aluminum alloy having various mechanical properties.

KEYWORDS

Additive manufacturing, Selective laser melting, Voronoi diagram, Aluminum foam, Energy absorption

INTRODUCTION

Additive manufacturing (AM) process enables to manufacture near net-shape mechanical parts. The AM technology is typically focused on titanium alloys due to their high specific strength and biocompatibility (Attar, 2014). Recently, aluminum alloy parts can be manufactured through selective laser melting method (Leary, 2016).

Metal foams or porous metals are lightweight cellular materials having closed- or open-cell structures (Banhart, 2001). Aluminum foams are focused on as an energy absorbing material for transport industries (Baumeister, 1997). The purpose of the present study is to investigate the optimal cell structure of open-cell porous aluminum alloy manufactured through AM process. Most previous researches on the AM aluminum lattice structure has been considered ordered and periodic cell structures. On the other hand, classical aluminum foams manufactured through cast or powder metallurgical processes have disordered and heterogeneous cell structures (Körner, 2000). The authors use a concept of Voronoi diagram (Moukarzel, 1993) in order to manufacture various cell structures.

Three kinds of cell structures were designed based on a 3D Voronoi diagram. Constructing process of 3D-CAD models are shown in Figure 1. First, a set of seed points are arranged in Eulerian coordinates (Figure 1(a)). Second, the Voronoi regions are generated based on the Voronoi geometry. Here, each polyhedron contains one seed point (Figure 1(b)). Third, the boundaries of Voronoi regions, Voronoi edges, are extracted (Figure 1(c)). Forth, the thickness of Voronoi edges are modified as an appropriate size (Figure 1(d)). Finally, the specimen is cut from the Voronoi diagram (Figure 1(e)). Then, the cell structure depends on the arrangement of a set of seed points. If the seed points are arranged to the random distribution, the resultant cell structure becomes disordered. If the seed points are arranged to the periodic and regular distribution, the resultant cell structure becomes ordered. The present study focusses on the difference of compressive properties between porous aluminum alloy specimens having ordered and disordered cell structures.

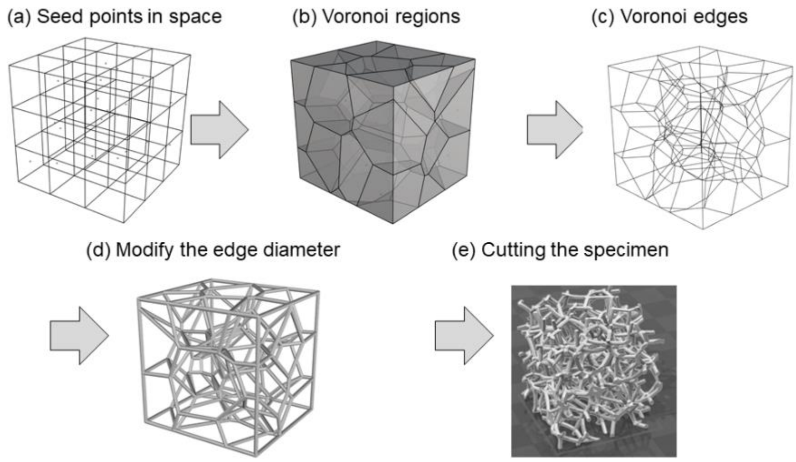

Figure 1. Construction process of 3D-CAD data based on Voronoi diagram

EXPERIMENTAL PROCEDURE

All 3D-CAD data were made by a 3D-CAD software, Rhinoceros 5. In the present study, two ordered cell structure, truncated octahedron and rhombic dodecahedron cells are constructed. Truncated octahedron cell structure was designed by body centered cubic, bcc, arrangements of seed points. Rhombic dodecahedron cell structure was designed by face centered cubic, fcc, arrangements of seed points. For disordered cell structure, the random cell structure was designed by random arrangements of seed points. Three 3D-CAD images of cubic specimens are shown in Figure 2. Nominal porosities are 90% in truncated octahedron and rhombic dodecahedron cell structures and 93% in truncated octahedron and random cell structures, which are calculated by volume of the solid elements. All cell struts have cylindrical shape with 1 mm in diameter. Since the truncated octahedron cell has 4-fold rotation symmetry, the top view is the same as the front view.

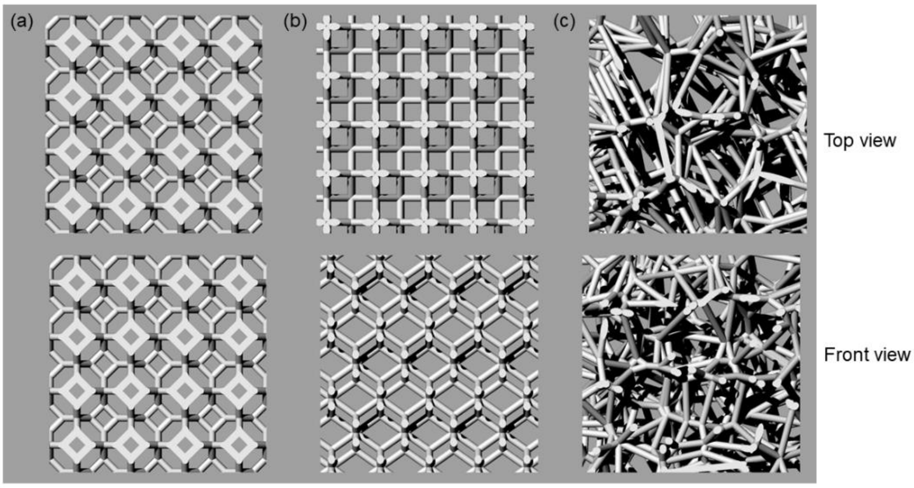

Figure 2. 3D-CAD images of (a) truncated octahedron cells, (b) rhombic dodecahedron cells and (c) random Voronoi cells

Compression specimens were manufactured through a powder bed fusion (PBF) machine, EOS M280, in Koiwai Co., Ltd., Japan (Figure 3). Al-10Si-0.3Mg alloy powder is used as a starting material. Building direction is parallel to the *z*-axis. Specimens have cubic shape with a side length of 30 mm. As-built specimens were annealed at 803 K for 6 h in air. Bulk density, ρ^*, was calculated from the total mass and the volume of the cubic. Practical porosity of each specimen is calculated as:

$$p = 1 - \frac{\rho^*}{\rho_S} \tag{1}$$

where ρ_S is the density of dense Al-10Si-0.3Mg alloy, 2670 kg/m^3. Because of the accuracy of AM process, the practical porosity became slightly high.

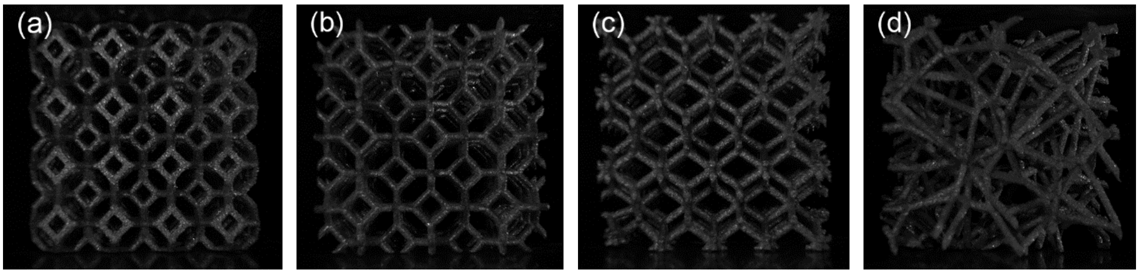

Figure 3. Images of porous Al-10Si-0.3Mg alloy specimens, (a) truncated octahedron cells, p = 91%, (b) truncated octahedron cells, p = 94%, (c) rhombic dodecahedron cells, p = 91%, (d) random Voronoi cells, p = 94%

Compression tests were carried out using a Shimadzu Autograph AG-50kNISD universal testing machine. Crosshead speed was fixed at 10 mm/min. No lubricant was used in compression tests.

RESULTS AND DISCUSSION

Results of compression tests are shown in Figure 4. Compression direction of the truncated octahedron cell structures is parallel to the building direction. Flow stress increased with decreasing the porosity. In the case of rhombic dodecahedron cell structures, the flow stress of the transverse direction was higher than that of longitudinal direction. Oscillations of the stress-strain curve shown in the transverse direction was due to the macroscopic shear band formation. Here, the longitudinal direction is parallel to the building direction.

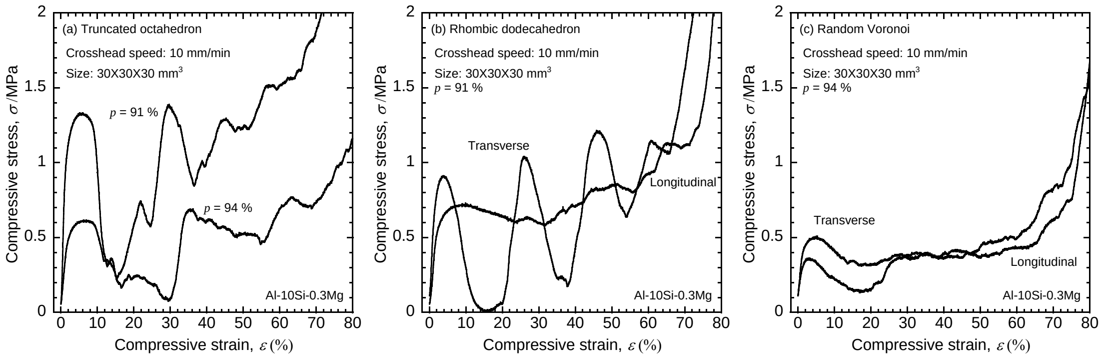

Figure 4. Compressive stress-strain curves of (a) truncated octahedron cells, (b) rhombic dodecahedron cells and (c) random Voronoi cells

In the case of random Voronoi cell structures, the flow stress of the transverse direction was higher than that of longitudinal direction. No oscillation was observed in the specimens with random Voronoi cell structure.

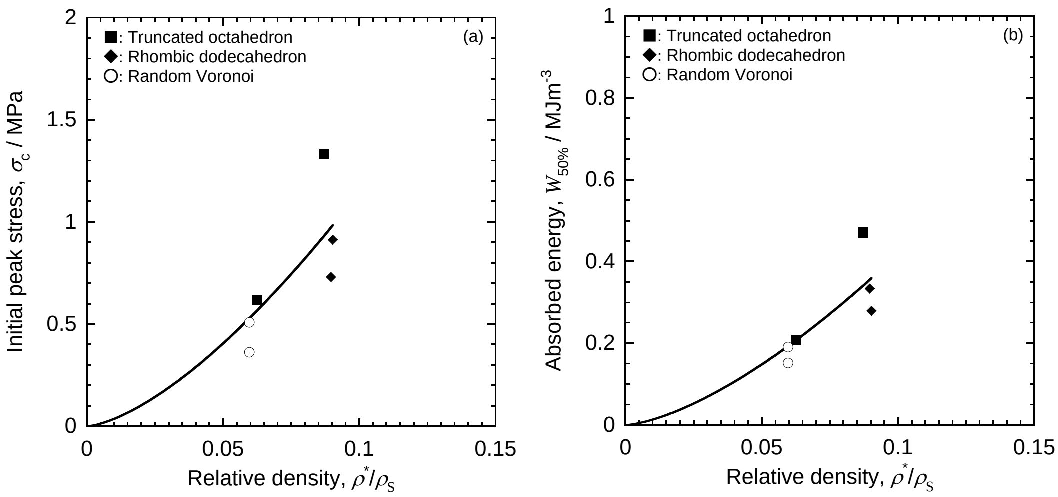

Figure 5. (a) Initial peak stress and (b) absorbed energy up to 50% strain are plotted as a function of relative density

Absorbed energy during the compressive deformation is expressed as

$$W = \int_0^{\varepsilon} \sigma \, \mathrm{d}\varepsilon \,. \tag{2}$$

In Figure 5, initial peak stress, σ_c, and energy absorption up to 50% strain, $W_{50\%}$, are plotted as a function of relative density. Solid curves show the Ashby's relationship (Ashby, 1983) for metal foams expressed as

$$\sigma_c = \sigma_0 \left(\frac{\rho^*}{\rho_S}\right)^{1.5}. \tag{3}$$

Both the initial peak stress and the absorbed energy in truncated octahedron cell structure were higher than those of others. Experimental results for the present aluminum foams were similar to the previous results for titanium foams (Yue, 2017). High strength shown in a truncated octahedron specimen is probably due to the shorter cell edge length of the truncated octahedron cell.

CONCLUSIONS

Porous Al-10Si-0.3Mg alloy specimens were manufactured through AM process. Two ordered cell structures, truncated octahedron and rhombic dodecahedron, and one disordered cell structure, random Voronoi, were designed using 3D-CAD software. Compression tests using cubic specimens revealed that the ordered cell structures have relatively high initial peak stress and absorbed energy. However, the deformation processes showed anisotropy and macroscopic shear band formation, which is not appropriate for structural applications. On the other hand, the specimen with random cell structure showed relatively isotropic deformation. Present results estimated that the partially disordered cell structures had a potential to mechanical applications compared to the completely ordered cell structures.

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