Accelerated Formation of an Ultrafine-Grained Microstructure in Closed-Cell Aluminum Foam after Extrusion and Differential Speed Rolling

W.Y. Kim¹, W.J. Kim²,* and H. Utsunomiya¹,*

¹Division of Materials and Manufacturing Science, Graduate School of Engineering, Osaka University, Suita 565–0871, Japan
²Department of Materials Science and Engineering, Hongik University, Mapo-gu, Sangsu-dong 72–1, Seoul 121–791, Republic of Korea

Plastic deformation by extrusion and high-ratio differential speed rolling on closed-cell aluminum foams resulted in the formation of ultrafine grains in the densified matrix. The microstructure had an average grain size of 1.30 μm and a fraction of high angle boundaries of 0.7. Under the same processing condition, only dynamic recovery occurred in the bulk aluminum. During deformation of the foam, continuous dynamic recrystallization accelerated at the cell walls due to the occurrence of a high degree of severe plastic deformation there. The bonded interfaces created by pore closure also provided a number of sites of high angle grain boundaries, thereby contributing to the grain refinement.

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1. Introduction

A metallic foam composed of solid metal gas-filled pores (with a typical porosity of 75–95%) can be used as a lightweight structure, energy absorber, heat exchanger, biomaterial or filter.¹ The metallic foams offer the advantage of high energy absorption by converting the impact energy into plastic deformation. Extensive studies have been conducted on the relationship between the strain, stress and energy-absorbing ability of the metallic foams.² ³ Recent works⁴ have shown that the plastic forming of porous metals has advantages in forming the machinery components with complicated shapes and improving the specific strength of the porous metals.

The effects of severe plastic deformation (SPD) on the microstructure and mechanical properties of pure aluminum and aluminum alloys have been extensively studied,² ³ but the associated studies on aluminum foams have been limited.

In this work, the changes in the microstructures of closed-cell aluminum foams after plastic deformation by extrusion or a combination of extrusion and high-ratio differential speed rolling (HRDSR) were examined, and the underlying mechanism for the accelerated grain refinement during deformation of metal foams was discussed.

2. Experimental

The aluminum foams with closed cells (ALPORAS) had a density of 0.279 Mg/m³, a cell size of 3.78 mm and a cell wall thickness of 0.15 mm. The cell size was measured by the intercept method over the square area (35 × 35 mm²) of the digital camera picture of the foam. The cell-wall thickness was measured by the averaging measurements at 10 different positions on the images taken by optical microscopy. The aluminum foam was machined to a cylinder shape and then placed inside a sheath tube made of A1070 aluminum (with an inner diameter of 9.0 mm) with one end is closed. The foam-filled tube was subsequently extruded at room temperature at the following three extrusion ratios: 2.4, 4.7 and 13.0. A more detailed description of the detailed extrusion procedures is available in Ref. 6), where the effect of the extrusion ratio on the density of the aluminum foam was reported.

Rods extruded at the relatively low ratios of 2.4 and 4.7 were subjected to warm rolling at 473 K for a thickness reduction from 7.0 or 5.1 to 3.0 mm through 1–2 passes by conventional rolling. After rolling, the materials were subjected to high-ratio differential speed rolling (HRDSR⁷ ⁸) with a roll speed ratio of 2, and a final thickness of 1 mm was obtained. During the HRDSR process, the surface temperature of the rolls was maintained at 473 K, and the samples were not preheated between passes. The samples obtained by the application of HRDSR to rods extruded at ratios of 2.4 and 4.7 will be hereafter referred to as HRDSR1 and HRDSR2, respectively.

The sample densities were determined from the measurements of weight and volume. The microstructures of the extruded and the HRDSR-processed samples were examined using an electron backscatter diffraction (EBSD) detector installed in a field emission SEM (JSM-6500F). The EBSD samples were cut off from the middle part of the extruded rods or sheets. For the HRDSR-processed samples, there can be a microstructural gradient along the thickness direction, though it was reported to be small.⁹ To avoid this concern, the microstructures of the sheath and foam were observed at the regions close to the interface between the foam and sheath in the upper part of the HRDSR-processed samples. The EBSD scan size was 50 × 40 μm and the scan step size was 0.2 μm. TSL version 5.2 was used as the analysis software, and data points with a confidence index lower than 0.05 were excluded from the EBSD data. The grain size was determined at tolerance angles of 15° (with threshold angle of 2°).

3. Results and Discussions

The longitudinal sections of the foam-filled tubes (1) before extrusion, (2) just prior to passing through the extrusion die, (3) during the flow through the die (with an extrusion ratio of 4.7) and (4) after HRDSR are shown in Fig. 1, togeth-
per with a schematic illustration of the experimental procedure. All foam cells were crushed in the extrusion container before the passage of the material through the die and became densified during the passage through the die. The aluminum foam after HRDSR, which lies in between the aluminum tube layers, appears to be highly compacted.

Figures 2(a) and (b) show an inverse pole figure (IPF) map of the as-received aluminum sheath and an SEM image (with an IPF map in right inset) of a cell wall in the as-received aluminum foam, respectively. The sheath has a fully recrystallized microstructure with an average grain size of 196 μm (Fig. 2(a)). The cell wall in the foam (Fig. 2(b)) shows a single orientation <101>/ND, indicating that the foam has an average grain size larger than thickness of the cell walls (0.15 mm).

Figures 2(c) and (d) show grain boundary (GB) maps superimposed on the image quality maps of the sheath and foam regions after the extrusion. In the maps, the grain boundaries are denoted by either blue lines corresponding to low-angle misorientations where the angle of misorientation, θ, is between 2° and 15° or red lines corresponding to high-angle misorientations with θ ≥ 15°. In Table 1, the average grain sizes, the fraction of high-angle grain boundaries and the average misorientation angles measured from the foam and sheath regions after deformation under the different processing conditions are presented. The grain size measured from the foam region after extrusion at a ratio of 13.0 was 1.86 μm, and the fraction of high-angle grain boundaries (HAGBs) was 0.60. Compared to these values, the grain size and the fraction of HAGBs measured from the sheath region were considerably larger (22.71 μm) and lower (0.16), respectively. This result indicates that during the extrusion, dynamic recovery occurred in the sheath, while continuous dynamic recrystallization (CDRX) occurred in the foam. It is known that CDRX is accelerated in aluminum under severe plastic deformation. Therefore, the above result suggests that a higher degree of SPD occurred in the aluminum foam than in the bulk aluminum. The deformation of metallic foams is typically divided into the following three stages: a linear elastic deformation stage, a plastic deformation and pore collapse stage, and finally a densification stage. Under uniaxial compression, the plastic deformation of closed-cell metal foams proceeds by the collective cell collapse (in bands) and strain localization by plastic buckling, bending, distortion, and shear at the cell walls and then propagation of cell crushing from one band to another. During the extrusion that accompanies a reduction in the cross-sectional area, more complicated deformation modes (including wrinkling and elongation of cells) and a larger shear amount of plastic deformation are expected to occur at the cell walls. It is interesting to note that the grain size and the fraction of HAGBs of the aluminum foam after extrusion are comparable to those (1.2 μm and 0.58) measured from the pure aluminum processed by equal channel angular extrusion (ECAE) after 4 passes at room temperature.

Figures 2(e) and (f) show grain boundary (GB) maps superimposed on the image quality maps of the sheath and foam regions after a combination of extrusion and HRDSR. The aluminum foam layer in HRDSR2 had a grain size of 1.96 μm and a fraction of HAGBs of 0.56 (Table 1). These values are comparable to those of the aluminum foam after extrusion at the high extrusion ratio of 13.0. The aluminum foam layer in HRDSR1, which suffered a larger deformation (by HRDSR) compared to that in HRDSR2, had a smaller grain size...
and a higher fraction of HAGBs (0.69). The grain size and the fraction of HAGBs of the sheath layers in HRDSR1 and HRDSR2 were, on the other hand, 6.06 μm - 0.31 and 9.29 μm - 0.23, respectively (Table 1). The relatively large grain sizes, the low fractions of HAGBs and the low average misorientation angles in the sheath layers in HRDSR1 and HRDSR2 indicate that the dynamic recovery still dominantly occurred in the bulk aluminum during the same HRDSR condition. This result supports that the foam obtained after a combination of extrusion and HRDSR has a unique microstructure.

Figure 3 shows a schematic illustration of the formation of an ultra/finer-grained microstructure with a high fraction of HAGB in the metal foam during extrusion and HRDSR. CDRX more accelerates in the foam than in the bulk during the extrusion and HRDSR processes because of the occurrence of additional plastic deformation caused by buckling, bending, distortion and wrinkling at the cell walls of foam. The bonded interfaces created by pore closure also provide a number of sites of HAGBs, thereby contributing to the grain refinement.

The densities of HRDSR1 and HRDSR2 were measured to be 2.49 and 2.59 Mg/m³, respectively. These values are lower than that of bulk aluminum of 2.7 Mg/m³. The failure to achieve the full density may be due to the resistance of the gas trapped inside the pores to pore closure during extrusion and HRDSR.

4. Conclusions

The application of a combination of extrusion and HRDSR to closed-cell aluminum foam resulted in the formation of ultrafine grains (1.3 μm) with a high fraction of HAGBs (0.69) in the densified matrix. This result suggests that the plastic deformation of a closed-cell aluminum foam can be an effective method for easily fabricating bulk materials with ultrafine grains with high fraction of HAGBs.

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