Graduate School of Fundamental Science and Engineering
Waseda University

博士論文概要
Doctoral Dissertation Synopsis

論文題目
Dissertation Title

Stabilization mechanism of pores in aluminum alloy foam during semi-solid route

セミソリッド発泡法で作製する際の発泡アルミニウム合金における気孔安定化メカニズム

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In recent years, there has been an increasing demand for lighter, more functional, and more durable materials to reduce environmental load. Aluminum alloy foams can satisfy these demands because they are ultralight and exhibit several mechanical properties, such as shock absorbance and heat isolation, because of their closed cell structure. Aluminum alloy foams are fabricated by adding TiH_2 as a blowing agent, which generates H_2 gas by thermal decomposition, into the melt and allowing the foam to solidify while retaining the bubbles. The uniformity and reproducibility of foams are essential for future industrial applications. However, the drainage at the cell wall decreases both uniformity and reproducibility of foams because the drainage ruptures the cell walls and leads to pore coarsening. The melt route, which is a conventional fabrication method, uses a thickening agent to increase the apparent viscosity of the melt, thereby preventing drainage. A semi-solid route does not use any additional thickening agent; instead, it crystalizes the primary crystals inherently included in the alloy, thereby discarding the need for adding impurity elements. The pore stabilization mechanism in the melt route and the preferred range for the fraction of thickening agent are already known. In contrast, the pore stabilization mechanism in the semi-solid route is unlike that of the melt route because the average diameter of the primary crystals is ten times larger than that of the thickening agent. This study focused on the semi-solid route and set an objective to reveal the stabilization mechanism of the semi-solid route to fabricate stable aluminum alloy foams.

According to a previous study on the semi-solid route, the primary crystals gather in the cell wall and prevent drainage physically. This mechanism is referred to as the clogging effect, which is considerably different from the pore stabilization mechanism of the melt route. However, there is still no clarity regarding why the primary crystals prevent the drainage and how many primary crystals are required to prevent the drainage in one cell wall. In addition, the clogging effect does not act over the entire foam. Percolation theory can provide clarity on both points because it indicates the minimum fraction of obstacles required to stop the liquid flow in any structure.

The prevention of drainage based on the clogging effect can improve both the uniformity and reproducibility of the foam. The volume fraction of solid varies easily with temperature, and therefore, the temperature of the semi-solid slurry during the foaming process in the semi-solid route can affect fabrication. Thus, even a small fluctuation in temperature can significantly affect the pore morphology of the foam. Therefore, the temperature fluctuation allowance needs to be identified to avoid changes in the pore morphology. The lower the concentration of oxygen during fabrication, the lower is the stability of the foam fabricated in the melt route. Furthermore, the reproducibility needs to be improved for comparative experiments to clarify the effect of oxygen.

The internal structure of the stable foam has gained considerable research attention. The X-ray computed tomography (CT) technique is commonly employed to observe the movement of pores during the compression test and the dynamics of the foaming process. However, no research has focused on the internal structure of the foam as one parameter quantitatively.

Chapter 1 provides an overview of aluminum alloy foams. The existing issues related to the mechanism of drainage prevention, reproducibility of the semi-solid route, and internal structure of the stable aluminum alloy foam are also discussed. Additional relevant topics, including the foam fabrication methods, internal structure of the foam, semi-solid processing, percolation theory, and Monte Carlo method, are also presented.

In Chapter 2, the objective was set to extend the clogging effect from the cell wall to the entire foam. The area fraction of the primary crystals in each cell wall of the fabricated aluminum alloy foam is measured, and the cell walls wherein the drainage is prevented by the clogging effect are referred to as clogged cell walls. According to the percolation theory, the clogged cell walls can be considered as obstacles for the drainage in the entire foam. Thus, the clogging effect works in both cell walls and the foam. Moreover, the clogged cell walls can ensure that the non-clogged cell walls do not develop drainage.

Chapter 3 reveals the preferred range of the primary crystals in volume fraction of solid and the effect of oxygen on the stability of the pores. Aluminum alloy foams were fabricated under same setting conditions or under different oxygen concentrations. The allowance fluctuation of the temperature was obtained for comparative experiments by fabricating five aluminum alloy foams under the same setting conditions. Three foams were compared under different temperature. The obtained results indicate that the number of clogged cell walls increases with an increase in the volume fraction of solid. Based on this result, the preferred range of the volume fraction of solid is calculated to be 15–35% of the volume fraction of solid. In addition, the area ratio of primary crystals in all cell walls increases, and therefore, a higher volume fraction of solids in the preferred range is considered to be more effective for pore stabilization. Foams fabricated under 18% oxygen and 10 ppm oxygen revealed that the oxygen in the furnace increased the stability of the pores and the primary crystals.

Chapter 4 defines the internal cell wall structure quantitatively. The internal cell wall structure is observed using X-ray CT. The new parameter, cell wall structure δ, is defined as the value obtained by subtracting the number of outflows connected to the drainage from the number of inflows. According to the Monte Carlo simulation, a larger value of δ has a smaller percolation threshold, which means that it is easy to prevent drainage. A pair distribution function $g(r)$ was obtained for each target cell wall structure δ to reveal the arrangement of the cell wall structure. Each cell wall structure δ was arranged to supplement the excess cell walls that do not connect to any cell walls.

Chapter 5 presents the three important conclusions of this thesis. Primary crystals whose presence exceeds the percolation threshold can prevent drainage in the entire foam. Therefore, the clogging effect can be applied not only to one cell wall but also to the entire foam. Further, the preferred range of the primary crystals in volume fraction is obtained as 15–35%. The clogging effect works more effectively with a higher volume fraction of solid in the preferred range. In addition, the allowance fluctuation of the temperature to fabricate the foam with high reproducibility is determined. Finally, it is determined that the oxygen in the atmosphere can improve the stability of the foam.

The findings of this study are expected to facilitate the commercial use of aluminum alloy foam. Methods to improve the uniformity and reproducibility of the foam are presented in this study. Therefore, a stable foam can be fabricated using the methods presented in this study. Further, stable aluminum foams with a variety of pore morphologies can be fabricated, and their mechanical properties can be measured. Finally, a safe and reliable society can be established because many products, such as transportation vehicles, heat exchangers, and architectural materials, use the foams. Moreover, the combination of the metal analysis tequnique and physical approach is expected to help establish new material processing techniques.

List of research achievements for application of Doctor of Engineering, Waseda University

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Journal (Corresponding)	○[1] Characteristics of Pore Morphology in Aluminum Alloy Foams Fabricated by Semi-Solid Route among Multiple Experimental Runs, Metals, September 2023, vol. 13, pp. 847-859, **S. Takamatsu**, T. Arai, A. Sayama and S. Suzuki
	○[2] Percolation of Primary Crystals in Cell Walls of Aluminum Alloy Foam via Semi-Solid Route, Metals, June 2020, vol. 10, pp. 1654-1669, **S. Takamatsu**, T. Kuwahara, R. Kochi and S. Suzuki
Jounal (Coauthor)	[3] Stabilization mechanism of semi-solid film simulating the cell wall during fabrication of aluminum foam, Metals, March 2020, vol. 10, pp. 333-345, T. Kuwahara, A. Kaya, T. Osaka, **S. Takamatsu** and S. Suzuki.
Oral presentation	[4] Aluminum alloy foams fabricated by semi-solid route in various atmosphere changing oxygen concentration, 145th JILM Annual Meeting, November 2023, **S. Takamatsu**, N. Tsuchida, M. Tsutsumi and S. Suzuki.
	[5] Relationship between Fabrication Conditions of Semi-solid Route and Morphology of Aluminum Alloy Foam, MetFoam2023 12th International Conference on Porous Metals and Metallic Foams, July 2023, **S. Takamatsu**, T. Arai, A. Sayama and S. Suzuki.
	[6] Effect of fabrication conditions of semi-solid route on stability of aluminum alloy foam, 143rd JILM Annual Meeting, November 2022, **S. Takamatsu**, T. Arai and S. Suzuki.
	[7] Stabilization Mechanism of Aluminum Alloy Foam affected by Primary Crystals and Cell Wall Structure, CellMAT2022 7th International Conference on Cellular Materials, October 2022, **S. Takamatsu**, T. Arai and S. Suzuki.
	[8] Effect of cell wall structure on stability of aluminum alloy foam, 142nd JILM Annual Meeting, May 2022, **S. Takamatsu**, T. Arai and S. Suzuki.
	[9] Stabilization mechanism and cell wall structure of alminum alloy foam in semi-solid route, 141st JILM Annual Meeting, November 2021, **S. Takamatsu**, T. Arai and S. Suzuki.
	[10] The Stabilization Mechanism of Semi-solid Foaming Method by Primary Crystals, MetFoam2019 11th International Conference on Porous Metals and Metallic Foams, August 2019, **S. Takamatsu**, T. Kuwahara, R. Kochi and S. Suzuki.
Poster presentation	[11] Pore morphology of aluminum alloy foam changing with fabrication conditions of semi-solid route, 144th JILM Annual Meeting, May 2023, **S. Takamatsu**, A. SAYAMA, T. ARAI and S. Suzuki.
	[12] Clogging effect with primary crystals in aluminum alloy foam based on percolation theory, 139th JILM Annual Meeting, November 2020, **S. Takamatsu**, T. Kuwahara, R. Kochi and S. Suzuki.
	[13] Stabilization mechanism of cell wall in aluminum alloy foamed in semi-solid state, 9th Porous Materials Research Symposium, March 2019, **S. Takamatsu**, T. Kuwahara, R. Kochi and S. Suzuki.
	[14] Stability of Cell Wall in Aluminum Alloy foamed in Semi-Solid State, 6th Poster Conference for Young Researcher JILM Kanto BRanch, August 2018, **S. Takamatsu**, T. Kuwahara, R. Kochi and S. Suzuki.
Lectures	[15] Application of semi-solid forming to fabrication of aluminum foam, Seminar at Technische Universitat Dortmund, July 2023, **S. Takamatsu**

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	[16] Allowance range of fabrication temperature for pore stabilization mechanism to work in semi-solid route, Seminar at Deutsches Zentrum fur Luft- und Raumfahrt (German Aerospace Center), July 2023, **S. Takamatsu**.
	[17] Recent Progress of Porous Metals in Japan, Seminar at Technische Universitat Berlin, October 2022, **S. Takamatsu**.
	[18] Recent progress in porous metals for aerospace and other applications, Seminar at Deutsches Zentrum fur Luft- und Raumfahrt (German Aerospace Center), October 2022, **S. Takamatsu**.
Award	[19] Excellent English Poster Award, 144th JILM Annual Meeting, May 2023, **S. Takamatsu**.
	[20] Excellent Materials Science Acdemic Award, Graduate School of Fundamental Science and Engineering Waseda University, March 2021, **S. Takamatsu**.
	[21] Excellent Student Award, 6th Poster Presentation of Young Scientists JILM Kanto Branch, August 2018, **S. Takamatsu**.
	[22] Excellent Woman Award, 6th Poster Presentation of Young Scientists JILM Kanto Branch, August 2018, **S. Takamatsu**.
	[23] JILM Kanto Branch Special Award, 6th Poster Presentation of Young Scientists JILM Kanto Branch, August 2018, **S. Takamatsu**.
	[24] JILM Kanto Branch Award, 6th Poster Presentation of Young Scientists JILM Kanto Branch, August 2018, **S. Takamatsu**.
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