Title	Specific Strength of Sandwich-Structured Composite of Open-Cell Metallic Foam/Resin Joined by Friction Stir Incremental Forming
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Specific strength of sandwich-structured composite of open-cell metallic foam/resin joined by friction stir incremental forming

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Abstract The compressive deformation behavior of an open-cell nickel foam joined with polymethyl methacrylate (PMMA) sheets by friction stir incremental forming (FSIF) process was investigated with uniaxial compression test. The sheet was joined on each side face of the foam for fabrication of the foam/sheet composite for uniaxial compression test. In FSIF process, the bottom of the sheet was mechanically interlocked to the surface pores of the foam by plastic flow of the frictionally heated sheet. In uniaxial compression test, the cubic foam/sheet composite was compressed with an initial strain rate of 1.0 x 10^{-3} s^{-1}. The compressive specific strength of the foam/sheet composite was approximately 30 times higher than that of the foam. This was due to not only high specific strength of the sheet but also the sandwich structure of the foam/sheet composite.

1 Introduction

Metallic foams are lightweight due to their low density, however, their strengths are generally low. In order to use metallic foams for structural components, improvement of the strength–mass relationship of component with metallic foam is essential. One of effective means for the improvement of the strength–mass relationship is sandwich-structured composite. Some fabrication processes for the sandwich-structured composite are proposed for foam materials. Concerning joining process of resin sheet on metallic foam or metal with porous surface, friction welding [1, 2], hot pressing [3], and incremental forming [4] have been reported. We applied friction stir incremental forming (FSIF) process to join resin sheet with open-cell foam [5]. The sheet was joined by mechanically interlocking to the porous structure of the foam by the plastic flow of the heated and softened resin sheet.

In this study, compressive deformation behavior of an open-cell type nickel foam joined with PMMA sheets by FSIF process is investigated with uniaxial compression test. The specific compressive strength of the sandwich-structured foam/sheet composite is compared with that of uniform mixture of nickel foam and PMMA.

2 Joining of Open-Cell Foam and Resin Sheet by Friction Stir Incremental Forming (FSIF)

Friction stir incremental forming (FSIF) process was originally developed for incremental sheet metal forming [6]. FSIF process was applied to join resin sheet with open-cell foam [5]. **Fig. 1** shows the schematic illustration of FSIF process for joining of open-cell foam and resin sheet. A rotating rod-shaped tool with a flat end is vertically pushed and horizontally fed against the sheet on the foam. The sheet is frictionally heated and incrementally deformed by the rotation and feed of the tool, while the foam is not plastically deformed.

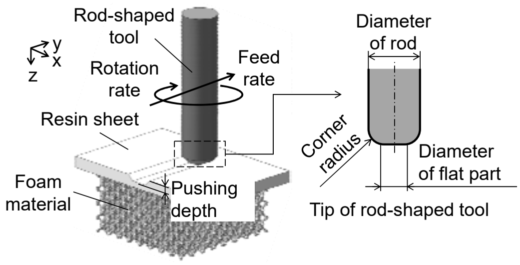

Fig. 1 Schematic illustration of friction stir incremental forming (FSIF) process for joining of open-cell foam and resin sheet [5].

3 Experimental Conditions

3.1 Open-Cell Foam and Resin Sheet

A commercial open-cell nickel foam (Celmet®, **Fig. 2a**) was used as substrate. The mean pore diameter and bulk density of the foam were 0.8 mm and ρ_f = 0.42 Mg/m^3, respectively. The relative density (bulk/buoyant density) was lower than 0.1. A commercial transparent polymethyl methacrylate (PMMA) sheet with a thickness of 1.0 mm (Delaglass^{TM} A) was used as resin. The density of the sheet was ρ_s = 1.19 Mg/m^3.

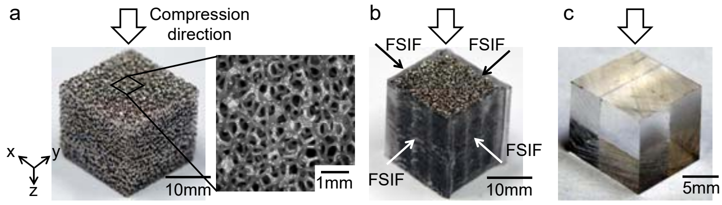

Fig. 2 Photographs of specimens for compression test. (a) open-cell nickel foam (Celmet®), (b) nickel foam/PMMA sheet composite, (c) PMMA.

3.2 FSIF Conditions

FSIF process was carried out for fabricating the nickel foam/PMMA composite specimen for compression test. In FSIF process, the flat end diameter of the tool was ϕ4 mm, and the tool was scanned with a rotation rate of 6000 rpm, a feed rate of 10 mm/min and a feed pitch of 4 mm, and a pushing depth of 0.5 mm.

The sheet was put on the foam with 15.5 mm x 15.5 mm x 20 mm in rectangular parallelepiped before FSIF process at each surface of the foam. FSIF process was carried out on the top face of the specimen. After finish of FSIF process on one face of the specimen, the specimen was turned from the top to the bottom or the side. Then FSIF process was carried out on new top face of the specimen. The sheet was joined on each side face of the foam with a cross-section of 15.5 mm x 15.5 mm by repeating this operation (**Fig. 2b**). After FSIF process, the specimen was cut with 16 mm x 16 mm x 16 mm in cube. The bulk density of the foam/sheet composite specimen was ρ_c = 0.59 Mg/m^3.

3.3 Compression Test Conditions

Compressive deformation behaviors of nickel foam without joining PMMA sheet, nickel foam joined with the PMMA sheets (nickel foam/PMMA sheet composite) and PMMA were investigated by uniaxial compression (**Fig. 2**). The initial shape of the foam and foam/sheet composite specimens was 16 mm x 16 mm x 16 mm in cube, while that of the PMMA specimen was 10 mm x 10 mm x 10 mm in cube. The specimens were compressed between mirror finish parallel platens with a speed of 1 mm/min under dry condition at room temperature.

The nominal compressive stress (σ) was calculated by dividing the compression load by the initial cross-sectional area of the specimen. The nominal compressive strain (ε) was calculated by dividing the crosshead stroke of the material testing machine by the initial height of the specimen.

4 Experimental Results

4.1 Interface of Foam/Resin

Fig. 3 shows the photograph and the element map of the cross-section of the interface of the nickel foam/PMMA sheet joined by FSIF process. Here the elements of nickel and carbon (PMMA) were detected by energy dispersive x-ray spectrometry (EDX) analysis. The PMMA sheet was confirmed to be plastically flowed into the surface pores of the foam. The mean flow thickness of PMMA was 0.56 mm. It is concluded that the nickel foam is mechanically interlocked with the PMMA sheet.

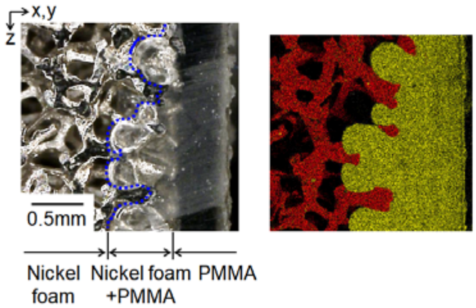

Fig. 3 Photograph and element map of cross-section of interface of nickel foam/PMMA sheet joined by FSIF process (red area: nickel, green area: carbon).

4.2 Compressive Deformation Behavior

Fig. 4 shows the photographs of the specimens during compression test. Due to buckling and bending of the cellular matrix of the foam, the plastic deformation was locally concentrated from the early stage of compression in the nickel foam specimen. In the nickel foam/PMMA sheet composite specimen, the delamination of the sheet from the foam occurred at early stage of compression due to bending of the sheet. After that, fracture of the sheet started.

The specific nominal compressive stress–strain curves of the specimens in compression test are shown in **Fig. 5**. Here each compression test was carried out with two specimens under the same conditions because of the scatters of the pore shape and size of the foam. The specific nominal compressive stress was calculated by dividing the nominal compressive stress (σ) by the initial bulk density (ρ) of the specimen. This is due to the removal of the influence of the weight of the specimen. The stress–strain curve of the foam specimen was lowest among that of the specimens, however, the stress increased with increasing strain. This is the typical deformation behavior of the foam [7]. The stress of the foam/sheet composite specimen increased with increasing strain of $\varepsilon < 0.05$–0.07. This is resulted from bending of the sheet. The stress was suddenly dropped after peaking at $\varepsilon = 0.05$–0.07 due to the fracture of the sheet, and then the stress was almost the same with that of the foam specimen. From the stress–strain curves, the specific nominal compressive stress of the foam (σ_f/ρ_f), foam/sheet composite (σ_c/ρ_c), and PMMA (σ_s/ρ_s) was 0.7 MPa·m^3/Mg, 22 MPa·m^3/Mg and 111 MPa·m^3/Mg at $\varepsilon = 0.05$, respectively. The specific strength of the foam–sheet composite was approximately 30 times higher than that of the foam.

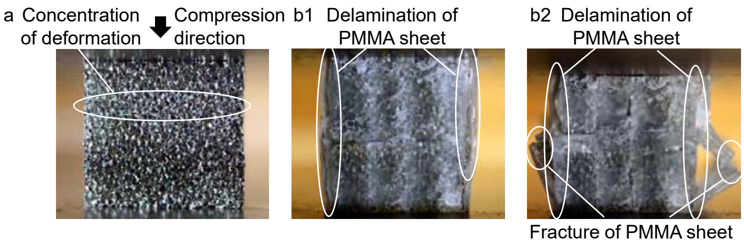

Fig. 4 Appearances of specimens during uniaxial compression. (a) nickel foam at nominal compressive strain $\varepsilon = 0.05$, (b1) nickel foam/PMMA sheet composite at $\varepsilon = 0.05$, (b2) nickel foam/PMMA sheet composite at $\varepsilon = 0.2$.

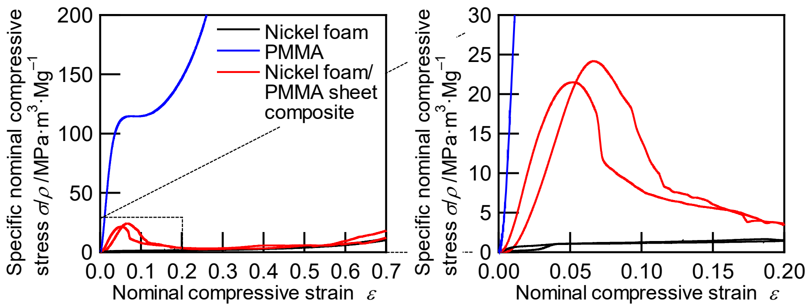

Fig. 5 Specific nominal compressive stress–strain curves of nickel foam, nickel foam/PMMA sheet composite, and PMMA in uniaxial compression.

5 Discussion on Improvement of Specific Strength of Nickel Foam/Resin Sheet Composite

The specific strength of the uniform mixture of nickel foam/PMMA was estimated by the following mixture rule:

$$X_{f\text{-}s} = \phi \cdot X_f + (1 - \phi) \cdot X_s \quad (1)$$

where $X_{f\text{-}s}$, X_f, and X_s were the properties (stress and bulk density) of uniform mixture of nickel foam/PMMA, nickel foam and PMMA, respectively. ϕ was the volume fraction of the nickel foam, and it was 0.87 in the nickel foam/PMMA sheet composite specimen for compression test.

The specific strength of the uniform mixture of nickel foam/PMMA was calculated as $\sigma_{f\text{-}s}/\rho_{f\text{-}s}$ = 14 MPa·m^3/Mg by **Eq. (1)**. The specific strength of the uniform mixture was lower than that of the foam/sheet composite (σ_c/ρ_c = 22 MPa·m^3/Mg, see section 4.2). Therefore the improvement of the specific strength of the foam/sheet composite was concluded to be due to not only high specific strength of PMMA but also sandwich structure with the sheet joined on the faces of the foam parallel to the compression direction.

6 Conclusion

The compressive deformation behavior of an open-cell type nickel foam joined with PMMA sheets by FSIF process was investigated with uniaxial compression test. The compressive specific strength of the foam/sheet composite was approximately 30 times higher than that of the foam. This was due to not only high specific strength of the sheet but also the sandwich structure of the foam/sheet composite. It is concluded the sandwich-structured composite of the foam joined with the sheet is effective to improve the strength–mass relationship.

Acknowledgment

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