Relationship between Porosity and Interface Fracture on Aluminum Foam Sandwich with Dense Steel Face Sheets Fabricated by Friction Stir Processing Route

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An aluminum foam sandwich consisting of an aluminum foam core with two dense metallic face sheets is expected to be used as a lightweight structural component with good energy and vibration absorption properties. In this study, by the friction stir processing route, aluminum foam sandwiches with porosity of approximately 55–85% and metallurgical bonding between the aluminum foam and dense steel sheets were successfully fabricated. Moreover, tensile tests were carried out on the fabricated aluminum foam sandwiches. Through the test results, it was shown that, although a brittle intermetallic compound layer exists at the interface, fracture in the aluminum foam part with porosity above 65% occurs and the bonding strength of the interface is higher than the tensile strength of the aluminum foam.

[doi:10.2320/matertrans.MAW201212]

(Received April 24, 2012; Accepted May 31, 2012; Published July 19, 2012)

Keywords: porous material, friction stir processing, foaming, bonding, composites, sandwich panel, tensile strength

1. Introduction

Aluminum foam is very lightweight and has good energy and vibration absorption properties. However, the tensile strength and bending strength of aluminum foam are lower than those of dense materials. Thus, an aluminum foam sandwich (AFS) structure consisting of an aluminum foam core with dense metallic face sheets is promising for use as a structural component.\(^1\),\(^2\) Although an AFS is usually fabricated by bonding an aluminum foam core to dense metallic sheets using an adhesive,\(^3\)–\(^5\) the use of an adhesive is limited owing to the difficulty in recycling\(^4\) and environmental problems.\(^5\) As a fabrication process without an adhesive, a powder metallurgical route using metallurgical bonding between aluminum foam and dense sheets has been proposed.\(^4\) In this route, after sufficiently mixing aluminum powder with a blowing agent, dense aluminum composites (i.e., foamy precursors) are fabricated by compacting the obtained mixture. Moreover, these foamy precursors are clad-bonded with two face sheets on both sides of the foam core by extrusion or rolling. However, the mixing and compacting of the powders and the extrusion (or rolling) are time-consuming processes; thus, the productivity of the foamy precursor is low.

Recently, the authors have applied the fabrication route of aluminum foam using friction stir processing (FSP) to fabricate the foamy precursor of an AFS.\(^7\)–\(^9\) In this route, using the FSP route precursor method,\(^10\),\(^11\) both the fabrication of a foamy precursor by mixing the blowing agent powder into aluminum sheets and metallurgical bonding between the foamy precursor and dense metallic sheets can be conducted simultaneously. Thus, it is expected that the foamy precursor for an AFS can be realized with high productivity. Moreover, using this process, we successfully fabricated an AFS of A1050 aluminum foam and SPCC low-carbon steel sheets with high porosity of approximately 80% and metallurgical bonding between the aluminum foam and dense steel face sheets.\(^9\) However, along the entire interface of the AFS, an Al–Fe intermetallic compound (IMC) layer with a thickness of several tens of micrometers was generated. The Al–Fe IMC layer is hard and brittle\(^12\),\(^13\) and is considered to greatly affect the strength of the bonding interface. Although the bonding strength of the interface was higher than the tensile strength of the aluminum foam of the AFS with a porosity of approximately 80% according to the results of a tensile test,\(^9\) the relationship between the tensile strength of aluminum foam with various porosities and the bonding strength of the interface of the AFS has not yet been quantitatively investigated.

In this study, an AFS consisting of A1050 aluminum foam and SPCC low-carbon steel sheets with a porosity of approximately 55–85% was fabricated by the FSP route while varying the amount of blowing agent. Tensile tests were carried out on the fabricated AFS, and the transition of the fracture type, i.e., whether fracture occurred from the aluminum foam part or the interface between the aluminum foam and dense steel face sheets, was observed for various porosities. Moreover, the bonding strength of the interface and the tensile strength of the aluminum foam part were compared, and the relationship between the tensile/bonding strength and the fracture type was examined. From these results, the porosity range for which interface fracture does not occur on an AFS fabricated by the FSP route is discussed.

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2. Experimental Procedure

2.1 Fabrication of aluminum foam sandwich (AFS)

Figure 1 shows a schematic illustration of the process of fabricating the foamable precursor for an AFS with high porosity (approximately 75–85%) by the FSP route. A1050 aluminum sheets of 2.5 and 2 mm thicknesses were used as sheets A and B, respectively, and an SPCC low-carbon steel sheet of 2 mm thickness was used as sheet C. Sheets A and B were laminated with blowing agent powder (TiH₂, < 45 µm) and stabilization agent powder (α-Al₂O₃, < 1 µm) distributed between them. The laminated sheets were stacked on sheet C, and FSP was conducted to mix the powders into the aluminum sheets and to join the laminated sheets. FSP was carried out using a friction stir welding machine (SHH204-720, Hitachi Setsubi Engineering Co., Ltd.). The tool used for FSP has a columnar shape with a screw probe. The diameter of the tool shoulder was 17 mm and the diameter of the tool probe was 6 mm. The tool rotation speed and the welding speed were 2200 rpm and 100 mm/min, respectively, with reference to a previous study on the fabrication of A1050 aluminum foam. A tilt angle of 3° was used with respect to the vertical axis of the sheet surface. As shown in Fig. 1(c), the probe depth of the rotating tool inserted into the surface of the steel was set to 0.2 mm with reference to a previous study on the fabrication of an aluminum foam/dense steel composite. Multipass FSP of 7 lines × 2 passes, as shown in Fig. 1(c), was applied to obtain a larger precursor and to mix the powders thoroughly. The amounts of TiH₂ powder were 0.6 and 1.0 mass% relative to the mass of the aluminum with dimensions of 165 mm × 35 mm × 5 mm (i.e., the area over which the powders were distributed and the length of the tool probe). The amount of Al₂O₃ powder was 5 mass% relative to the mass of the aluminum with the same dimensions. Foamable precursors of aluminum with dimensions of 35 mm × 35 mm × 4.5 mm bonded with 80 mm × 35 mm × 2 mm steel sheets were cut from the region subjected to FSP.

Figure 2 shows a schematic illustration of the fabrication process of the foamable precursor for an AFS with comparatively low porosity (approximately 55–65%). In this case, amounts of TiH₂ powder of 0.05, 0.1 and 0.2 mass% were used. Owing to the low expansion efficiency during the heating process and because of the small amounts of TiH₂ powder, a laminated precursor consisting of four aluminum sheets was used to obtain a large AFS. The amount of Al₂O₃ powder was 5 mass%. After following the process shown in Figs. 1(a) and 1(b) with the above amounts of TiH₂ powder and Al₂O₃ powder, as shown in Figs. 2(a) and 2(b), A1050 aluminum sheets D of 2 mm thickness and E of 1.5 mm thickness were laminated with the same amounts of TiH₂ powder and α-Al₂O₃ powder distributed between them and were stacked on laminated sheets A, B and C joined by FSP. As shown in Figs. 2(c) and 2(e), multilass FSP of 7 lines × 2 passes was conducted for laminated sheets D and E with the same tool rotation speed, welding speed and tool tilt angle as before. The probe depth of the rotating tool inserted into the surface of steel A was approximately 1.3 mm, and laminated aluminum sheets D and E were joined to laminated sheets A, B and C. Foamable precursors of aluminum with dimensions

![Fig. 1 Schematic illustration of fabrication process of foamable precursor for aluminum foam sandwich (AFS) with high porosity by FSP route.](image1)

![Fig. 2 Schematic illustration of fabrication process of foamable precursor for aluminum foam sandwich (AFS) with comparatively low porosity by FSP route.](image2)
of $35\,\text{mm} \times 35\,\text{mm} \times 4.5\,\text{mm}$ bonded with $80\,\text{mm} \times 35\,\text{mm} \times 2\,\text{mm}$ dense steel sheets were cut from the region subjected to FSP.

Figure 3 shows a schematic illustration of the foaming process of the foamy precursors. As shown in Fig. 3(a), two precursors were placed face to face in a die. The distance between the steel sheets of the two precursors with 0.2, 0.6 and 1.0 mass% TiH$_2$ was 30 mm, that for the precursors with 0.1 mass% TiH$_2$ was 20 mm and that for the precursors with 0.05 mass% TiH$_2$ was 16 mm. Then, the foamy precursors were heated in a preheated electric furnace. The holding temperature (equal to the preheated temperature) was 1003 K (730°C). The holding time during the heating process was that required to obtain sufficient expansion (the highest porosity) of the foamy precursor, which was determined by checking the foaming state of the precursor from 540 s in steps of 30 s. The holding time was 570 s for the precursors with 0.6 and 1.0 mass% TiH$_2$ and 810 s for the precursors with 0.05, 0.1 and 0.2 mass% TiH$_2$. After heating, the precursor was cooled to room temperature under ambient conditions. AFS specimens of $30\,\text{mm} \times 30\,\text{mm} \times 34\,\text{mm}$ (a cubic aluminum foam part of $30\,\text{mm}$ length with $2\,\text{mm}$ dense steel sheets on both sides) for 0.2, 0.6 and 1.0 mass% TiH$_2$, $30\,\text{mm} \times 30\,\text{mm} \times 24\,\text{mm}$ (a $30\,\text{mm} \times 30\,\text{mm} \times 20\,\text{mm}$ aluminum foam part with $2\,\text{mm}$ dense steel sheets on both sides) for 0.1 mass% TiH$_2$ and $30\,\text{mm} \times 30\,\text{mm} \times 20\,\text{mm}$ (a $30\,\text{mm} \times 30\,\text{mm} \times 16\,\text{mm}$ aluminum foam part with $2\,\text{mm}$ dense steel sheets on both sides) for 0.05 mass% TiH$_2$ were cut by electro-discharge machining.

2.2 Evaluation of pore structures

The porosity $p$ (%) of each AFS specimen was calculated by the following equation:

$$p = \frac{\rho_i - \rho_f}{\rho_i} \times 100,$$

where $\rho_i$ is the density of the foamy precursor without dense steel sheets before heating and $\rho_f$ is the density of the aluminum foam part of the AFS specimen. The density of pure aluminum$^{15}$ is used for $\rho_i$. $\rho_f$ was evaluated as follows. First, the mass of the AFS specimen with dense steel sheets $m_{\text{AFS}}$ was measured. Next, by multiplying the density of steel$^{19}$ and the volume of the two dense steel sheets, the mass of the two dense steel sheets $m_{\text{STL}}$ was estimated. Finally, $\rho_f$ was evaluated by the following equation:

$$\rho_f = \frac{m_{\text{AFS}} - m_{\text{STL}}}{V_{\text{AFP}}},$$

where $V_{\text{AFP}}$ is the volume of the aluminum foam part of the AFS specimen.

To evaluate the pore structure of the aluminum foam part, the AFS specimens were scanned by a microfocus X-ray CT system (SMX-225CT, Shimadzu Corporation). The X-ray source was tungsten in this system. The X-ray tube voltage and current used in the inspection were 80 kV and 30 $\mu$A, respectively. The resolution of the X-ray CT image was $512 \times 512$ pixels and the length of one pixel was approximately 88.5 $\mu$m. An appropriate threshold was set for all the two-dimensional cross-sectional X-ray CT images to distinguish the aluminum and the pores to obtain binarized X-ray CT images of the pore structures. From the binarized X-ray CT images, the equivalent diameter $d$ was evaluated by the following equation using image-processing software (WinROOF, Mitani Corporation):

$$d = 2\left(\frac{A}{\pi}\right)^{\frac{1}{2}},$$

where $A$ is the area of each pore. In the evaluations, pores with area less than $1.0\,\text{mm}^2$ were excluded owing to the resolution of the X-ray CT images. Moreover, the average equivalent diameter $d_m$ was calculated from the average values of $d$ for all pores in each AFS specimen.

2.3 Tensile tests on AFS specimen

A part for gripping during tensile tests was realized by bonding a jig using an adhesive to the dense steel sheets of the AFS specimens. The tensile tests were carried out at room temperature using an Instron type testing machine with a load capacity of 98 kN. The relative velocity between the cross head and the screw rod was set at 1 mm/min.

3. Results and Discussion

3.1 Porosity and pore structures

As examples, Figs. 4(a) and 4(b) show a fabricated AFS specimen with a porosity of 58.0% and its typical X-ray CT image, and Figs. 5(a) and 5(b) show a specimen with a porosity of 83.6% and its X-ray CT image, respectively. The upper and lower parts of the X-ray CT image are the dense steel sheets, and the other part shows the cell wall of the aluminum foam. We consider that oxide films on the surfaces of foamy precursors broke into comparatively small film owing to the expansion and bonding of the precursors, the broken films were mixed in aluminum and two precursors were fully combined in the foaming process. Then, in the
uniformly (cf. Figs. 1(a) and 2(a)) owing to the very small amount of TiH₂ powder, resulting in the differences in the amount of TiH₂ powder contained in the precursor with the location where the precursor was cut. As shown in Fig. 7, above a porosity of approximately 65%, the value of \( d_m \) increased with increasing \( p \), whereas when \( p \) was below approximately 65%, \( d_m \) was almost constant (approximately 1.6 mm) regardless of the value of \( p \). From the results, it is considered that when \( p \) is below approximately 65%, its value was mainly determined by the number of pores. The equivalent diameter of the AFS with a porosity of approximately 85% was approximately equal to that of ALPORAS, a commercially available porous aluminum.

### 3.2 Results of tensile tests and discussion

As examples of typical tensile stress–strain curves of AFS specimens with both low porosity and comparatively high porosity, Fig. 8(a) shows those for porosities of 58.0 and 76.3%. Figures 8(b)–8(g) show photographs of the specimens corresponding to positions (b)–(g) in Fig. 8(a). When the porosity was low, no local fracture occurred below the maximum tensile stress, and interface fracture (brittle fracture) occurred suddenly at the point where the tensile stress became the maximum (cf. Fig. 8(c)). When the porosity was comparatively high, little local fracture occurred below the maximum tensile stress and, although the fracture surface cannot be seen in Fig. 8(e), local fracture of the cell wall began to occur immediately after the tensile stress became the maximum. After that, the tensile stress gradually decreased with increasing tensile strain owing to crack propagation by the continuous plastic deformation and fracture of the cell wall (cf. Fig. 8(f)) then the final fracture occurred (cf. Fig. 8(g)). The tensile strength of the AFS specimen with low porosity was higher than that of the AFS specimen with comparatively high porosity.

Figure 9(a) shows the relationship between the porosity \( p \) and tensile strength \( \sigma_t \) for three types of fracture (i.e., fracture in the aluminum foam, fracture in the aluminum foam accompanied by partial interface fracture and interface fracture). In this figure, the result of a previous study is also shown. When \( p \) was approximately 65–85%, the value of \( \sigma_t \) increased with decreasing \( p \) as shown by the solid line in Fig. 9(a). In contrast, it is considered that the fracture strength of the IMC layer was almost the same regardless of the porosity because the same foaming conditions (holding temperature of 1003 K and holding time of 570 s) were employed. As shown by the double-dot-dashed line, the fracture strength of the IMC layer was higher than the tensile strength of the aluminum foam; thus, it can be considered that the fracture in the aluminum foam shown in Fig. 8(g) occurred similarly to that in the AFS specimen in the previous study. Moreover, the value of \( \sigma_t \) for this range of \( p \) represents the tensile strength of the aluminum foam. However, it is considered that the composition and thickness of the IMC layer may change with holding temperature and holding time, and further examinations are necessary on the variations of composition, thickness and bonding strength of the IMC layer by foaming condition.

When \( p \) was 62.5%, both fracture in the aluminum foam and interface fracture occurred as shown in Fig. 9(b). This suggests that the fracture strength of aluminum foam is almost similar to that of the AFS specimen.
AFS specimen was fabricated with a holding time of 810 s. The thickness of the IMC layer tended to increase with increasing holding time; thus, it was assumed that the fracture strength of the IMC layer decreased to some degree. It is considered that, in the AFS sample with a porosity of 62.5%, the fracture strength of the IMC layer became nearly equal to the increased tensile strength of the aluminum foam with decreasing $p$, and that the value of $\sigma_T$ simultaneously represents the bonding strength of the interface and the tensile strength of the aluminum foam.

When $p$ was below approximately 60%, only interface fracture occurred as shown in Fig. 8(c). AFS specimens with such values of $p$ were also fabricated with a holding time of 810 s and, therefore, the fracture strength of the IMC layer was almost the same regardless of the porosity. Although the variation in $\sigma_T$ was rather large owing to the brittleness of the IMC layer, it can be considered that the value of $\sigma_T$, which represents the bonding strength of the interface, was also almost constant as shown by the dot-dashed line in Fig. 9(a). On the other hand, when $p$ was below approximately 60%, it was found that the tensile strength of the aluminum foam increased with decreasing porosity as shown by the broken line in Fig. 9(a). Then, the tensile strength of the aluminum foam became higher than the fracture strength of the IMC layer, and it was considered that only interface fracture occurred.

From these results, when an AFS consisting of an aluminum foam core with two dense steel face sheets was fabricated by the FSP route, although a brittle IMC layer exists at the interface, it was shown that the bonding strength of the interface was higher than the tensile strength of the aluminum foam part with porosity larger than approximately 65%. As aluminum foam with comparatively high porosity is used as commercially available porous aluminum, it is expected that, if the aluminum foam part has the porosity larger than approximately 70%, an AFS with highly reliable interface bonding...
(i.e., without the occurrence of interface fracture) between the aluminum foam and dense steel face sheets can be fabricated by the FSP route.

4. Conclusions

In this study, an AFS with a porosity of approximately 55–85% and metallurgical bonding between the aluminum foam and dense steel sheets was fabricated. Moreover, as the Al–Fe intermetallic compound layer along the interface is brittle and greatly affect the tensile strength of the AFS, tensile tests were carried out on the fabricated AFS specimens. The tensile strength of the aluminum foam was compared with the bonding strength of the interface. The experimental results led to the following conclusions.

1. At a porosity of approximately 65–85%, the bonding strength of the interface was higher than the tensile strength of the aluminum foam, and fracture occurred in the aluminum foam.

2. When the porosity was 62.5%, the fracture in the aluminum foam was accompanied by partial interface fracture. The bonding strength of the interface became nearly equal to the tensile strength of the aluminum foam core.

3. At a porosity below approximately 60%, only interface fracture occurred. The tensile strength of the aluminum foam became higher than the bonding strength of the interface.

4. It is expected that, if the aluminum foam core has a high porosity of larger than approximately 70%, i.e., that of commonly used porous aluminum, an AFS with highly reliable interface bonding between the aluminum foam and dense steel face sheets can be fabricated by the FSP route.

Acknowledgments

The authors thank former Associate Professor T. Yokota, Shibaura Institute of Technology, and Professor K. Saito, Gunma University, for their helpful advice on conducting the experiments, and former Professor H. Kumehara, Gunma University, for fruitful discussions throughout this study. This work was financially supported partly by JKA promotion funds from AUTORACE and the Industrial Technology Research Grant Program in 2009 from the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

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