Aluminum alloy foam core sandwich panels fabricated from die casting aluminum alloy by friction stir welding route

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Abstract

An aluminum foam sandwiches (AFSs) consisting of ADC12 Al-Si-Cu die casting aluminum alloy foam and ADC6 Al-Mg die casting aluminum alloy face plates were fabricated. Using ADC12 die casting plates containing large amounts of gases as the starting material of the foam, ADC12 foam can be fabricated without using a blowing agent. Using FSW, both the uniform dispersion of the segregated gases and pore stabilization powder in the ADC12 die casting plates used to fabricate a foamable ADC12 precursor and the bonding of the ADC12 precursor to the ADC6 plates can be simultaneously achieved. Namely, the AFS precursor is expected to be obtained in fewer processing steps. From the visual observation of the fabricated AFSs, no deformation of the ADC6 plates occurred and the ADC6 plates on both sides of the aluminum foam remained parallel. From the X-ray CT observation of the fabricated AFSs, good pore structures without the infiltration of ADC12 foam into the ADC6 plates can be obtained at a holding temperature of 948 K and holding times of $t = 10$ and 11 min. In tensile tests on the fabricated AFSs, fracture occurred in the ADC12 foam parts but no fractures were observed at the bonding interface between the ADC12 foam and the ADC6 plates, that is, good bonding was obtained between the ADC12 foam and the ADC6 plates.

Keywords : cellular materials; die casting; friction stir welding; tomography; sandwich panel; foam

1. Introduction

Aluminum foam is expected to be used for components of automobiles owing to its light weight and superior energy absorption properties. An aluminum foam sandwich (AFS) is a product consisting of an aluminum foam core and two dense metallic face plates. The outer metallic plates improve the tensile and bending strengths of the aluminum foam, as described by **Gibson, (2000)** and **Banhart, (2005)**. **Banhart, (2001)** and **Banhart and Seeliger, (2008)** reviewed various manufacturing processes for AFSs. AFSs are usually fabricated by bonding an aluminum foam core to dense metallic plates using an adhesive. **Chen et al., (2001)** fabricated an AFS consisting of a closed-cell aluminum foam with the trade name ALPORAS, of which fabrication process was described by **Miyoshi et al., (2000)**, and commercial-purity aluminum plates bonded by epoxy adhesive. **McCormack et al., (2001)** fabricated an AFS consisting of ALPORAS and A6061-T6 aluminum alloy plates bonded using a commercially available structural adhesive. However, the use of an adhesive prevents AFSs from being used at high temperatures, decreases their recyclability and has raised considerable environmental concerns, as pointed out by **Barnes and Pashby, (2000)**. **Baumeister et al., (1994)** proposed a metallurgical bonding process for AFSs. In this process, a foamable precursor, which is a sintered mixture of aluminum powder and blowing agent powder, is first fabricated. Thereafter, the foamable precursor is clad-bonded with dense metallic plates by extrusion or rolling. The foamable precursor is expanded by heat treatment to obtain a metallurgically bonded AFS. **Banhart and Seeliger, (2008)** and **Banhart and Seeliger, (2012)** reviewed this clad-bonding process for fabricating AFSs, and also described the current applications of AFSs. They commented that the high cost of AFSs prevents their use in a wider range of applications. To reduce the cost of AFSs, a fabrication process without the use of aluminum powder as a starting material that also combines various process steps into fewer integrated steps should be developed.

Hangai et al., (2010b) demonstrated that a foamable precursor can be fabricated from aluminum plates as the starting material using friction stir welding (FSW). FSW is a solid-state process that generates intense plastic deformation, as reviewed by **Mishra and Ma, (2005)** and **Ma, (2008)**. In this fabrication process using FSW, two aluminum plates are first stacked with blowing agent powder and pore stabilization agent powder distributed between them. Next, the blowing agent powder and pore stabilization agent powder are mixed into the aluminum plates by FSW to obtain a foamable precursor. FSW was primarily developed for the bonding of aluminum plates. **Cederqvist and Reynolds, (2001)**, **Soundararajan et al., (2007)** and many other researchers have demonstrated that a lap joint of dissimilar aluminum alloys can be produced by FSW. **Hangai et al., (2010a)** proposed a new processing route that can be used to simultaneously fabricate a foamable precursor and achieve metallurgical bonding between the precursor and a dense metallic plate by FSW. **Hangai et al., (2012a)** and **Utsunomiya et al., (2012)** successfully fabricated an AFS consisting of A1050 commercial-purity aluminum foam and SPCC low-carbon steel plates by the FSW route. Although an Al-Fe intermetallic compound layer consisting of Fe_2Al_5 and FeAl_3 was generated at the interface between the A1050 foam and the SPCC plates, tensile tests on the AFS revealed that the bonding strength of the interface was relatively high compared with the tensile strength of the A1050 foam part with porosity above 65%. **Utsunomiya et al., (2013)** fabricated an all-aluminum AFS consisting of ADC12 Al-Si-Cu aluminum alloy foam and A1050 plates. It is expected that a reduced weight can be achieved by using low-density aluminum face plates instead of steel face plates. It was indicated that the bonding strength of ADC12 foam and A1050 plates was higher than the tensile strength of ADC12 foam with porosity above 50%.

Aluminum alloy high-pressure die castings have received considerable attention in the automotive field owing to their high productivity and high recycling efficiency. In

the die casting process, the formation of gas pores and dissolved gases in aluminum alloy potentially occurs during foundry production, as described by **Walkington, (2006)**. The source of these gases comprises gases existing in the cavity, runners and injection system, and also the reaction gases formed when melted aluminum alloy encounters the releasing agent and lubricant used in production. **Hangai et al., (2012b)** demonstrated that these gases can be used for foaming instead of using a blowing agent, which is relatively expensive and an explosion hazard. In this process, FSW was used to uniformly mix the segregated gases in the die casting plates and to mix the pore stabilization agent powder into the die casting plates to fabricate the precursor of the Al foam. By heat treatment of the precursor, aluminum foams with porosity of 50 - 77% were successfully fabricated without the use of a blowing agent. **Utsunomiya et al., (2011)** and **Hangai et al., (2012c)** revealed that the pore diameter is smaller and the sphericity of pores is higher than those of aluminum foam fabricated using a blowing agent. If an AFS is fabricated from aluminum alloy die castings as the starting material, its recyclability and cost are expected to be markedly improved.

In this study, AFSs consisting of ADC12 Al-Si-Cu die casting aluminum alloy foam, fabricated without using a blowing agent, and dense ADC6 Al-Mg die casting aluminum alloy plates were fabricated by the FSW route. Both the fabrication of the ADC12 foam precursor and the bonding between the ADC12 precursor and the ADC6 plates were simultaneously conducted by FSW. ADC12 has superior mechanical properties and castability, and is widely available but has low corrosion resistance. In contrast, ADC6 has superior corrosion resistance. Therefore, the combination of an ADC12 foam core and ADC6 face plates is expected to improve not only the cost efficiency, recyclability and specific strength but also the corrosion resistance of AFSs. The solidus temperature is relatively similar for ADC12 and ADC6 (788 and 863 K, respectively). It is of concern that ADC6 face plates may soften during the foaming process, causing their

deformation and a reduction of their thickness, by the infiltration of ADC12 foam into the ADC6 plates. The holding time was optimized to ensure sufficient foaming to obtain AFSs with relatively high porosity and good pore structures without deformation or a reduction of the thickness of the face plates. The pore structures and the reduction of thickness of the face plates of the fabricated AFSs were nondestructively and three-dimensionally observed by X-ray computed tomography (CT) in a quantitative evaluation. In addition, tensile tests were conducted on the fabricated AFSs to confirm that sufficient bonding between the ADC12 foam and the ADC6 plates was achieved.

2. Experimental procedure

2.1 Fabrication of AFS

As the starting material of the Al foam, ADC12 aluminum alloy die casting plates of 3 mm thickness were used, which were fabricated using a cold-chamber die casting machine. Fig. 1(a) shows the conventional die casting setups usually used for mass

Fig. 1. Schematic illustration of die casting setups for fabricating ADC12 aluminum alloy die casting plates. (a) Conventional setups for mass production. (b) Setups used in this study.

Table 1. Types and amounts of gases in ADC12 aluminum alloy die casting plates (cm³/100 gAl).

	H ₂	N ₂	CH ₄	CO	CO ₂	C ₂ H ₄	Total
Conventional	1.2	6.1	0.9	-	1.6	-	9.7
This study	122.5	64.4	16.3	32.3	78.3	1.5	315.6

Table 2. Chemical composition of die casting aluminum alloy used in this study (mass%).

	Cu	Si	Mg	Zn	Fe	Mn	Ni	Sn	Al
ADC12	1.72	10.14	0.18	0.56	0.82	0.27	0.04	0.02	Bal.
ADC6	0.01	0.68	3.26	0.06	0.53	0.42	0.01	0.00	Bal.

production. Fig. 1(b) shows the die casting setups used in this study for fabricating ADC12 plates containing large amounts of gases. There are several differences between the setups. First, to incorporate the gases existing in the cavity, runners and injection system into ADC12 plates, the air vent was closed by welding the top of the die. Second, a lubricant instead of a release agent was applied on the die, and the air blast process employed after applying the lubricant to remove excess lubricant was not employed. This was to generate a large amount of reaction gases, which form when melted aluminum alloy encounters the lubricant.

Table 1 shows the types and amounts of gases in the die casting plates fabricated with the die casting setups shown in Fig. 1, which were measured by gas chromatographic analysis after melting the die casting plates. The source of N₂ gas is considered to be air existing in the cavity, runners and injection system. In contrast, the source of H₂ and other gases such as CH₄ is considered to be the reaction gases formed when the melted aluminum alloy encounters the release agent and lubricant. It can be seen that the amounts of all gases increased when the die casting setups shown in Fig. 1(b) was applied. As the starting material of the face plates, ADC6 die casting aluminum alloy plates of 3 mm thickness were used. Table 2 shows the chemical composition of ADC12 and ADC6 die casting aluminum alloy used in this study.

Fig. 2 shows a schematic illustration of the AFS fabrication process by the FSW route. First, as shown in Fig. 2(a), ADC12 plates were laminated with a pore stabilization agent powder ($\alpha\text{-Al}_2\text{O}_3$, $\sim 1\ \mu\text{m}$, 5 mass%) placed between them. The laminated plates were stacked on an ADC6 plate, and FSW was conducted to uniformly mix the gases and powder into the ADC12 plates and to join the laminated plates, as shown in Figs. 2(b) and (c). FSW was carried out using an FSW machine manufactured by Hitachi Setsubi Engineering Co., Ltd. (Hitachi, Japan). The FSW tool had a cylindrical shape with a screw probe. The diameter of the tool shoulder was 17 mm, and the diameter of the tool probe was 6 mm and its length was 5 mm. SKH51 high-speed tool steel was used as the tool material. The tool rotation speed was 1000 rpm and the welding speed was 100 mm/min. The tool axis was tilted by 3° with respect to the vertical axis of the plate surface. The multipass FSW technique, which **Sato et al., (2005)** demonstrated by shifting the traversing direction of the FSW tool to obtain a larger amount of precursor

Fig. 2. Schematic illustration of aluminum foam sandwich (AFS) fabrication process by FSW.

(five lines in this study) and **El-Rayes and El-Danaf, (2012)** demonstrated by overlapping the passes of the FSW tool to mix the gases and powders thoroughly (four times in this study) as shown in Fig. 2(c), was applied. The probe depth of the rotating tool inserted into the surface of the ADC6 plate was set to 0.2 mm at the FSW of last time.

As shown in Fig. 2(d), precursor samples of 25 mm × 20 mm × 5 mm ADC12 bonded with a 80 mm × 20 mm × 3 mm ADC6 plate were machined from the region subjected to FSW. As shown in Fig. 2(e), two precursors were placed face to face in the die. The precursor samples were then heated in a preheated electric furnace to induce foaming. The holding temperature (equal to the preheated temperature) during the foaming process was fixed at 948 K. The holding time during the foaming process was varied from 8 to 13 min in steps of 1 min. After heating, the sample was cooled to room temperature under ambient conditions. Two samples were foamed for each holding time except for 13 min. The foamed samples were cut by electrodischarge machining to obtain tensile test specimens.

2.2 Evaluation of pore structures of ADC12 foam and thickness of ADC6 plates

The porosity p (%) of the ADC12 foam part of each AFS was evaluated as

$$p = \frac{\rho_i - \rho_f}{\rho_i} \times 100, \quad (1)$$

where ρ_i is the density of the precursor without an ADC6 plate before heat treatment and ρ_f is the density of the ADC12 foam part of the AFS. The density of ADC12 aluminum alloy given in **The-Japan-Institute-of-Light-Metals, (1991)** was used for ρ_i . ρ_f was evaluated as follows. First, the mass of the AFS with an ADC6 plate, m_{AFS} , was measured. Next, the mass of the ADC6 plates, m_{plate} , was estimated by multiplying the density of the ADC6 plates given in **The-Japan-Institute-of-Light-Metals, (1991)** by

the volume of the ADC6 plates, V_{plate} , of the AFS tensile test specimen. Finally, ρ_f was evaluated as

$$\rho_f = \frac{m_{\text{AFS}} - m_{\text{plate}}}{V_{\text{AFS}} - V_{\text{plate}}}, \quad (2)$$

where V_{AFS} is the volume of the AFS tensile test specimen.

To evaluate the equivalent diameter and circularity of the pores of the ADC12 foam, X-ray CT observations were performed on the tensile test specimen using an SMX-225CT microfocus X-ray CT system (Shimadzu Corporation). The X-ray source was tungsten. A cone-type CT system, which produces three-dimensional images, was employed. In this system, only one rotation of the specimen was sufficient to obtain a three-dimensional volume image, which consisted of a set of two-dimensional cross-sectional X-ray CT images with the slice pitch equal to the length of one pixel in the X-ray CT image. The resolution of each CT image was 512×512 and the pixel length was approximately $50 \mu\text{m}$. The X-ray tube voltage and current were 80 kV and $30 \mu\text{A}$, respectively.

The average equivalent diameter, d_a , and average circularity, e_a , of the pores were evaluated from two-dimensional cross-sectional X-ray CT images of the ADC12 foam parts parallel to the ADC6 plates using WinROOF image processing software (Mitani Corporation). An appropriate threshold was set to distinguish the cell walls and the pores, and binarized X-ray CT images were constructed for the evaluation. Pores with areas of less than 0.4 mm^2 were excluded from the evaluation owing to the resolution of the X-ray CT images, as discussed by **Hangai et al., (2009)**. The equivalent diameter, d , and circularity, e , of a pore were evaluated as

$$d = 2 \left(\frac{A}{\pi} \right)^{\frac{1}{2}}, \quad (3)$$

$$e = \frac{4\pi A}{L^2}, \quad (4)$$

where A is the pore area and L is the pore perimeter. A value of circularity closer to 1 indicates a more circular pore.

The thickness of the ADC6 plates of each AFS was evaluated from the two-dimensional cross-sectional X-ray CT images of the AFS parallel to the ADC6 plates. Using the X-ray CT images, the thickness of the ADC6 plates of the entire AFS can be evaluated. The number of slices of X-ray CT images of the ADC6 plate part in which there was no infiltration of pores of ADC12 foam was counted. The thickness of the ADC6 plates was determined by multiplying the number of slices by the slice pitch of the X-ray CT images. The thicknesses of both the upper and lower ADC6 plates were evaluated and the lower thickness was determined as the thickness of the ADC6 plates of the specimen.

2.3 Tensile tests

The size of the tensile test specimens was 15 mm × 15 mm × 21 mm (the cubic ADC12 foam part had a side length of 15 mm and the ADC6 plates on both the upper and lower sides had a thickness of 3 mm). The size of the tensile specimen was selected such that the length of a side of the ADC12 foam part was more than 10 times the average equivalent pore diameter, d_a , to suppress the edge effect in accordance with JIS-H-7902, (2008). The grip part used in the tensile tests was formed by attaching a jig to the dense ADC6 plates of the AFS using a structural adhesive. The tensile tests were carried out at room temperature using a universal testing machine. The relative velocity between the cross head and the screw rod was set at 1.5 mm/min. Strain was defined as displacement of cross head of the universal testing machine divided by the initial length of ADC12 foam. During the tensile tests, the tensile behavior of the specimen was

recorded on a digital video camera.

3. Experimental Results and Discussion

3.1 Fabricated AFSs

Fig. 3 shows a cross section of the AFS precursor, as shown in Fig. 2(d) perpendicular to the FSW direction. It can be seen that good bonding between the ADC12 precursor and the ADC6 plate was achieved. Also, Al_2O_3 powder, which appeared as white cloudlike regions in the ADC12 precursor, was distributed almost uniformly in the ADC12 precursor. Therefore, it was shown that the AFS precursor was fabricated simultaneously with both the fabrication of the ADC12 precursor and the bonding of the ADC12 precursor to the ADC6 plates by FSW.

Fig. 4 shows the fabricated AFS tensile test specimen with an ADC12 foam part of porosity $p = 70.3\%$ before attaching a jig. No cracklike cavities were observed in the ADC12 foam where the bonding of two ADC12 precursors occurred during the foaming

Fig. 3. Cross section of the precursor of the AFS perpendicular to the FSW direction.

Fig. 4. Fabricated AFS tensile test specimen with porosity of 70.3% before attaching a jig.

process, as shown in Fig. 2(e), or at the interface between the ADC12 foam and the ADC6 plates. Also, no deformation was observed for the ADC6 plates, and the two ADC6 plates remained parallel after conducting FSW and the foaming process. This is because, although the holding temperature set in this study (948 K) was higher than the solidus temperature of the ADC6 plates (863 K), the holding time was short for the ADC6 plates to undergo softening. Also, the foaming force pressed the ADC6 plates so that they fit the foaming jig, therefore the ADC6 plates remained parallel after the foaming process. Consequently, it was shown that a sound AFS can be obtained through the FSW route.

Fig. 5 shows the relationship between the holding time and the porosity of the ADC12 foam part of the fabricated AFSs. It can be seen that the porosity of the AFSs increased with increasing holding time. If the holding time was short, aluminum matrix was not sufficiently softened for the pores to grow and expand the aluminum matrix. Therefore, by increasing holding time, the porosity gradually increased. The variation of the porosity at the same holding time is considered to be due to the segregated distribution of the gases in one ADC12 plate and the variation of the amount of gases in each ADC12 plate. Such variation can be reduced by further optimizing the die casting conditions to achieve a uniform gas distribution in one ADC12 plate and the same amount of gases in each ADC12 plate.

Fig. 5. Relationship between holding time and porosity of ADC12 foam part of fabricated AFSs.

3.2 Pore structures of ADC12 foam and thickness of ADC6 plates

Fig. 6 shows photographs of the surface of the AFS tensile test specimens fabricated with various holding times before attaching a jig. Fig. 7 shows typical two-dimensional X-ray CT reconstructed images of approximately central cross sections of the AFSs shown in Fig. 6. The upper and lower white parts indicate the ADC6 plates and the other white parts indicate the cell walls of the ADC12 foam. For a low holding time, as shown

Fig. 6. Photographs of surface of AFSs fabricated with various holding times, t . (a) $t = 8$ min. (b) $t = 10$ min. (c) $t = 12$ min.

Fig. 7. X-ray CT images of central cross sections of fabricated AFSs in Fig. 6. (a) $t = 8$ min. (b) $t = 10$ min. (c) $t = 12$ min.

in Figs. 6(a) and 7(a), it can be seen that the pores were small, there were cracklike pores and the porosity was low. These results indicate that the ADC12 was not sufficiently softened for the pores to grow and expand the ADC12. For a holding time of $t = 10$ min, as shown in Figs. 6(b) and 7(b), almost all the pores had a highly spherical shape and were distributed almost homogeneously, with the porosity exceeding 70%. When the holding time was high, as shown in Figs. 6(c) and 7(c), sufficient expansion of the ADC12 occurred and high porosity of approximately 80% was obtained. However, the generated pores coalesced into large pores, and the ADC12 foam began to infiltrate into the ADC6 plates, especially at the surface of the AFS as shown in Fig. 6(c).

Fig. 8(a) shows the relationship between the holding time, t , and the average equivalent diameter of pores, d_a , in the AFSs. It can be seen that the pore diameter increased with the holding time, which is the same tendency as the relationship between the holding time and the porosity shown in Fig. 5 and also consistent with the photographs and X-ray CT images of the AFSs shown in Figs. 6 and 7.

Fig. 8(b) shows the relationship between the holding time, t , and the average circularity of

Fig. 8. (a) Relationship between holding time, t , and average equivalent diameter of pores, d_a , in AFSs. (b) Relationship between holding time, t , and average circularity of pores, e_a , in AFSs.

pores, e_a , in the AFSs. It can be seen that the maximum circularity of the pores was achieved at holding times of $t = 10$ and 11 min. When the holding time was 9 min or less, the foaming was not sufficient and cracklike pores, which appeared before the generation of pores, were seen, as shown in Figs. 6(a) and 7(a). Therefore, the circularity of pores was low. When the holding time was 12 min or more, the coalescence of pores started to occur and the porosity increased. However, the coalescence of pores distorted the pore shape, as shown in Figs. 6(c) and 7(c). Therefore, the circularity of the pores started to decrease.

Fig. 9 shows the relationship between the holding time, t , and the normalized minimum thickness of the ADC6 plates, th , of the fabricated AFSs. It can be seen that the thickness of the ADC6 plates remained almost constant up to a holding time of $t = 11$ min. In contrast, the thickness of the ADC6 plates decreased when the holding time was increased to $t = 12$ min and above, which is consistent with Figs. 6(c) and 7(c). The decrease in the thickness of the face plates of an AFS causes its mechanical properties to deteriorate. Therefore, it was shown that a sound AFS without a decrease in thickness of the ADC6 plates can be obtained at a holding time of 11 min or less. Here, the thickness

Fig. 9. Relationship between holding time, t , and normalized minimum thickness, th , of ADC6 plates of fabricated AFSs.

of the ADC6 plates for holding times of up to $t = 11$ min was less than the initial thickness of the plates. This is because FSW was conducted by inserting the tool probe into the surface of the ADC6 plates, as shown in Fig. 2(c), meaning that pores were also generated at the surface of the ADC6 plates during the foaming process.

Consequently, it was shown that holding times of $t = 10$ and 11 min were suitable for the AFSs obtained in this study from the viewpoint of good pore structures and sound ADC6 face plates.

3.3 Tensile tests

Fig. 10(a) shows the typical tensile stress-strain curve of the obtained AFS fabricated with a holding time $t = 10$ min with porosity $p = 70.3\%$. The tensile stress sharply

Fig. 10. Results of tensile tests on AFS fabricated at $t = 10$ min with porosity $p = 70.3\%$. (a) Stress-strain curve of obtained AFS and photographs of (b) initial state, (c) state immediately after maximum stress was applied and (d) final state.

dropped immediately after the maximum tensile stress was applied. Figs. 10(b) - (d) show digital images obtained during the tensile tests. Fracture occurred from the ADC12 foam part, as shown in Fig. 10(d), indicating that the bonding strength of the interface was higher than the tensile strength of the ADC12 foam part. This tendency was observed for all the specimens fabricated in this study regardless of the holding time and porosity.

Fig. 11 shows the relationship between the porosity, p , and the maximum tensile strength, σ_T , of the fabricated AFSs. It can be seen that the tensile strength decreased with increasing porosity, except below $p = 65\%$. The tensile strength of the AFS is the tensile strength of the ADC12 foam itself in this case. Therefore, it is considered that the tensile strength of the AFS increased because the cross-sectional area of the ADC12 part increased as the porosity decreased. The tensile strength increased with 1.5 power of the relative density of ADC12 foams in this study. Compressive tests of ADC12 foams conducted by Hangai et al., (2012b) revealed the plateau stress increased with 1.3 power of the relative density of ADC12 foams with porosity of 50-77%. However, the tensile strength markedly decreased below $p = 65\%$. Fig. 12 shows the fracture path and fracture surface of AFSs after tensile tests for the cases of $t = 8$ min ($p = 60.4\%$) and $t =$

Fig. 11. Relationship between porosity, p , and tensile strength, σ_T , of fabricated AFSs.

10 min ($p = 70.3\%$). As shown in Figs. 12(a) and (c), the fracture path for the case of $t = 8$ min was flat compared with that for the case of $t = 10$ min. As shown in Fig. 12(b), the surface of the ADC12 precursors remained along almost the entire fracture surface for $t = 8$ min. In contrast, as shown in Fig. 12(d), fracture occurred at the cell walls of the foam for $t = 10$ min. This indicates that the decrease in tensile strength of the AFS fabricated with $t = 8$ min was mainly due to the insufficient bonding of two precursors during the foaming process.

These results show that holding times of $t = 10$ and 11 min were suitable for fabricating a sound AFS consisting of ADC12 foam and ADC6 plates at a holding temperature of 948 K. It is expected that the proposed FSW route will be effective for fabricating an AFS with highly reliable interface bonding. It is considered that there is a threshold porosity at which the lower strength shifts from the aluminum foam part to the bonding interface between the ADC12 foam and the ADC6 plates if sufficient bonding between two precursors is achieved at a low porosity. A sound AFS may be fabricated by increasing the amount of precursor, such as by increasing the thickness of the

Fig. 12. Fracture path and fracture surface after tensile tests on AFSs. (a) and (b) Holding time $t = 8$ min. (c) and (d) Holding time $t = 10$ min.

precursor by using three ADC12 plates during FSW as shown in Fig. 2(a). Clearly, much more extensive studies are necessary to examine the porosity of the foam part to investigate the applicability of AFSs fabricated by the FSW route.

4. Conclusions

In this study, AFSs consisting of ADC12 die casting aluminum alloy foam and ADC6 die casting aluminum alloy face plates, were fabricated by the FSW route. The porosity of the ADC12 foam part of the fabricated AFSs increased as the holding time was increased from 8 to 13 min at a holding temperature of 948 K. No deformation of the ADC6 plates was observed and the ADC6 plates on both sides of the aluminum foam remained parallel for all the AFSs fabricated in this study. From the visual surface observation and X-ray CT observation of the fabricated AFSs, it was shown that the infiltration of ADC12 foam into the ADC6 plates occurred at holding times of 12 min and above. Tensile tests on the fabricated AFSs with porosity from 60 to 85% revealed that fracture occurred in the ADC12 foam parts for all the AFS tensile test specimens, and no fractures were observed at the bonding interface between the ADC12 foam and the ADC6 plates. Therefore, good bonding between the ADC12 foam and the ADC6 plates was obtained by FSW.

Acknowledgments

This work was supported by JST Accelerating Utilization of University in 2013.

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Figure captions

Fig. 1. Schematic illustration of die casting setups for fabricating ADC12 aluminum alloy die casting plates. (a) Conventional setups for mass production. (b) Setups used in this study.

Fig. 2. Schematic illustration of aluminum foam sandwich (AFS) fabrication process by FSW.

Fig. 3. Cross section of the precursor of the AFS perpendicular to the FSW direction.

Fig. 4. Fabricated AFS tensile test specimen with porosity of 70.3% before attaching a jig.

Fig. 5. Relationship between holding time and porosity of ADC12 foam part of fabricated AFSs.

Fig. 6. Photographs of surface of AFSs fabricated with various holding times, t . (a) $t = 8$ min. (b) $t = 10$ min. (c) $t = 12$ min.

Fig. 7. X-ray CT images of central cross sections of fabricated AFSs in Fig. 6. (a) $t = 8$ min. (b) $t = 10$ min. (c) $t = 12$ min.

Fig. 8. (a) Relationship between holding time, t , and average equivalent diameter of pores, d_a , in AFSs. (b) Relationship between holding time, t , and average circularity of pores, e_a , in AFSs.

Fig. 9. Relationship between holding time, t , and normalized minimum thickness, th , of ADC6 plates of fabricated AFSs.

Fig. 10. Results of tensile tests on AFS fabricated at $t = 10$ min with porosity $p = 70.3\%$. (a) Stress-strain curve of obtained AFS and photographs of (b) initial state, (c) state immediately after maximum stress was applied and (d) final state.

Fig. 11. Relationship between porosity, p , and tensile strength, σ_T , of fabricated AFSs.

Fig. 12. Fracture path and fracture surface after tensile tests on AFSs. (a) and (b) Holding time $t = 8$ min. (c) and (d) Holding time $t = 10$ min.

Table 1. Types and amounts of gases in ADC12 aluminum alloy die casting plates ($\text{cm}^3/100 \text{ gAl}$).

Table 2. Chemical composition of die casting aluminum alloy used in this study (mass%).