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Effects of foam core density and face-sheet thickness on the mechanical properties of aluminum foam sandwich

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Abstract. To study the effects of foam core density and face-sheet thickness on the mechanical properties and failure modes of aluminum foam sandwich (AFS) beam, especially when the aluminum foam core is made in aluminum alloy and the face sheet thickness is less than 1.5 mm, three-point bending tests were investigated experimentally by using WDW-50E electronic universal tensile testing machine. Load–displacement curves were recorded to understand the mechanical response and photographs were taken to capture the deformation process of the composite structures. Results demonstrated that when foam core was combined with face-sheet thickness of 0.8 mm, its carrying capacity improved with the increase of core density. But when the thickness of face-sheet increased from 0.8 mm to 1.2 mm, result was opposite. For AFS with the same core density, their carrying capacity increased with the face-sheet thickness, but failure modes of thin face-sheet AFS were completely different from the thick face-sheet AFS. There were three failure modes in the present research: yield damage of both core and bottom face-sheet (Failure mode I), yield damage of foam core (Failure mode II), debonding between the adhesive interface (Failure mode III).

Keywords: aluminum foam sandwich; three-point bending; mechanical properties; deformation; failure mode

1. Introduction

Metal foams are a new class of materials with low densities and novel physical, mechanical, thermal, electrical and acoustic properties such as good stiffness and strength to weight ratios, high energy absorption, thermal and sound insulation (Gibson and Ashby 1997, Ashby *et al*. 2000, Gibson 2000). Among metal foams, aluminum foams have been extensively used in engineering fields like aerospace, automobile and architecture especially for its lightweight and energy absorption properties (Banhart and Seeliger 2008, Lu and Ong 2001). For a number of years, researchers have studied on the mechanical and physical properties of pure aluminum foams. Results showed that the comprehensive mechanical properties of pure aluminum foams were not high enough to meet the requirements of industrial applications, while its physical properties were excellent (Duarte *et al*. 2014, Nammi *et al*. 2010, Huang *et al*. 2012). These concerns, in order to

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improve the mechanical strength and use the special function of aluminum foam, aluminum foam composites have been developed in recent years.

Aluminum foam sandwich structure is one of the popular aluminum foam composites constituted of aluminum foam core and two dense metal cover sheets (Fe, Al or Ti alloy, etc) in general. Because of the special structure, sandwich composites allowed for a unique combination of energy absorption through large deformations within the foam core and a high flexural strength through the face-sheets themselves and thus can be used in weight-sensitive structures like components used in aerospace, automotive and shipbuilding industry (Banhart 2001, Baumeister *et al*. 1997, Thoma *et al*. 2004). There are two main preparation methods for AFS: adhesive method and powder metallurgy method. Adhesive method is using adhesive to glue the face-sheet and foam core together. The interfacial connection type between face-sheet and foam core is physical connection. Powder metallurgy method is blending the heated raw powder materials of core together and then put the blending power into a prepared container. The container is also used as face-sheet. After the container is packed tightly, foam the foamable precursor by proper technology to get the AFS. The interfacial relation between face-sheet and foam core is metallurgical bonding by this method. The first method is more acceptable for its lower cost and simpler craft as compared with the second one, which is proved to be stronger in the interfacial connection but costs more (Thoma *et al*. 2004, Wei *et al*. 2003, Zu *et al*. 2012, Duarte *et al*. 2015).

Many studies in recent years have focused on the fabrication of aluminum foam sandwich structure. The effects of different parameters have also been studied in detail. Zu *et al*. (2012) produced an AFS by powder metallurgy method. The mechanical behavior and failure modes of the new AFS were discussed. Crupi *et al*. 2013 studied on one commercial AFS with the faces bonded to the core by an epoxy adhesive under three-point bending conditions and the results showed that the capacity of energy absorption under bending load was affected by the collapse mechanism and also by the face-core bonding and the cell size of foam. Also it depended on the quality and mechanical properties of the foam core materials. However, the reason for this performance had not been explained amply. Styles *et al*. 2008 studied on the core thickness effects on AFS under flexural loading through finite element model, the results illustrated that the peak load of core with 5 mm thickness was significantly lower than the 20 mm one. That means the peak load increases with the thickness of foam core. According to Liu *et al*. 2013, blast tests were performed on aluminum foam–steel panel sandwich composites with different aluminum foam core densities. Results indicated that the ratio of the peak load was incident to the sandwich structure and the peak load transmitted from the sandwich structure increased with the decrease of foam core density. According to Zu *et al*. 2013, the maximum bending load of aluminum foam-steel panel sandwich structure increased with the thickness of both steel panel and foam core under three-point conditions. D'Alessandro *et al*. 2014 established a new model for aluminum foam sandwich panels based on the experimental tests to study the vibrational performances of AFS panels. Ruan *et al*. 2010 studied on the closed cell aluminum foam core-aluminum face-sheet sandwich panels and the effects of face-sheet thickness, core thickness, boundary condition, adhesive and surface condition of face-sheets on the mechanical response and energy absorption of sandwich panels were discussed. Kabir *et al*. 2014 investigated the very thin face sheets aluminum foam-cored sandwich composites. Result showed that the peak load of panel thickness with 12 mm was higher than that of panel thickness with 6 mm. Peak load increased with panel thickness. Duarte *et al*. 2016 studied on the mechanical characteristic of a new kind of al-alloy foam composite made by incorporating steel bar into the foam structure during the foaming process. Apart from mechanical properties, failure mode is also an important research topic in AFS. Three competing failure modes, namely core shear, core indentation and face sheet cracking were identified under four point bending of sandwich beams consisting of alumina face sheet and Alporas foam core by Mohan *et al*. 2005. But from McCormack *et al*. 2001, there were five failure modes in Sandwich beams having aluminum foam core and aluminum face sheets, can fail in five modes: face yielding, face wrinkling, core shear, core indentation and delamination. Different failure modes appeared in different studies, this depended on the fabrication process, test condition and geometric sizes. Previous studies focused on AFS with various core and face-sheet materials, but to the authors' knowledge, there is little reported documents investigated into AFS with aluminum face-sheet thickness less than 1.0 mm. Under the rules of design criteria of composites aluminum face-sheet with thickness less than 1.0 mm is feasible and reasonable.

In this present work, AFS made of aluminum alloy foam core with density of 0.73 g/cm^3, 0.56 g/cm^3, 0.49 g/cm^3 and aluminum alloy face-sheet with thickness of 0.8 mm, 1.0 mm, 1.2 mm respectively was investigated to study the effects of foam density and face sheet thickness on the quasi-static mechanical properties and failure mode in aluminum foam sandwich. Specimens were tested under three-point bending condition and observed during the tests. Results showed that face-sheet thickness had remarkable influence on the bending strength and failure mode of AFS beams.

2. Experimental method

2.1 Preparation of aluminum foam sandwich beams

7050 matrix closed-cell aluminum foams were selected as the core of sandwich structure. The chemical compositional limits of matrix material were shown in Table 1. The density of 7050 aluminum alloy is 2.83 g/cm^3. Tensile strength, yield strength and hardness of matrix alloy are 490 MPa, 420 MPa, 135 HB respectively by commercial supplied. To investigate the influence of aluminum foam density, three types of aluminum foams were employed with relative density of0.73g/cm^3, 0.56 g/cm^3, 0.49 g/cm^3. The closed-cell aluminum alloy foams were fabricated by the melt foaming method and the yield strength of foam cores were 8.8 MPa, 4.4 MPa, 4.17 MPa respectively. In order to study the effect of face-sheet thickness on sandwich structure, 6061 aluminum alloy panels with thickness of 0.8 mm, 1.0 mm, 1.2 mm were chosen as face-sheets. The tensile strength of 6061 alloy is more than 180 MPa and the yield strength is more than 110 MPa. E44 resin and 650 resin firming agent were selected as adhesive. E44 is a bisphenol A type epoxy resin and 650 is polyamide resin.

The foam-only beams were cut from large as-received panels with the thickness of 15 mm to the required dimensions (150 mm × 30 mm) using a saw equipment. A fixture and guide were used to ensure that the sizes were right and the surfaces were plane-parallel. The aluminum panels were cut to the same size as foam-only samples in length and width by wire cutting machine. To provide better adhesion, bonded surfaces of both the foam samples and aluminum sheet samples were degreased and abraded. The degreasing process was accomplished by immersing the aluminum sheets and the foam beams in two baths of alcohol. They were washed in the first bath and rinsed in the second one. The liquid in the baths were changed after they became visually contaminated.

Table 1 Chemical Composition Limit of 7050 Aluminum Alloy (wt%)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	others	Al
≤ 0.12	0.15	2.2	0.04	2.3	0.06	5.7~6.7	0.05	0.15	margin

The abrading process was finished by rubbing the surfaces with sandpaper. In addition, the surfaces to be bonded were cleaned using a brush and cloth artificially. Since alcohol entered into the voids during the degreasing process, the aluminum foam specimens were dried by hair drier. After the aluminum foam samples and the aluminum alloy face-sheet samples prepared well completely, they were bonded by using epoxy resin and its firming agent in the order of aluminum alloy sheet – aluminum foam – aluminum alloy sheet carefully. The epoxy resin and firming agent stayed in hot water bath at 60℃ for 40 minutes and then blended at the mass ratio of 1:1 before used. The fabricated sandwich specimens were pressed under a certain press force to ensure the adhesive surfaces were touched closely. The adhesive film was solidified at room temperature more than 48 hours.

2.2 Three-point bending test

Specimens were loaded in a three-point bending configuration as shown in Fig. 1 with WDW-50E electronic universal tensile testing machine. Tests were carried out with span lengths, *l*, of 80 mm and the overhang distance beyond the outer support, *H*, was 35 mm. The indenter moved at rate of 2 mm/min to indent the specimen at the midpoint of the top face-sheet. Diameter of the indenter was 10 mm (*a* = 10 mm). Specimen was simply supported on two support pins with the diameter of 10 mm. The loads, *P*, and the indenter displacements, *S*, were recorded by the computer connected to the WDW-50E automatically. The thickness of aluminum core, *c*, was 15 mm and the total thickness of the specimen, *d*, was 17.5, mm on average. All specimens were tested under the same condition. Photographs were taken to record the deformation of foam cores and both face sheets during tests.

To study the influence of core density on the mechanical properties of AFS, three groups of experiments were conducted under three-point bend. Specimens of the first group were aluminum foam only beams with densities of 0.73 g/cm^3, 0.56 g/cm^3, 0.49 g/cm^3 respectively. The second

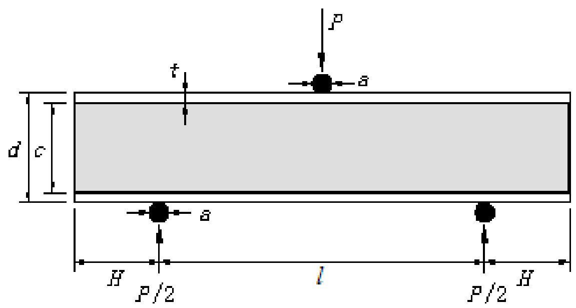

Fig. 1 Sandwich beam under three-point bending

Table 2 Numbers of specimens

Thickness/ mm Density/ g/cm^3	--	0.8	1.2
0.73	1-1	2-1	3-1
0.56	1-2	2-2	3-2
0.49	1-3	2-3	3-3

Table 3 Numbers of specimens

Thickness/ mm Density/ g/cm^3	--	0.8	1.2
0.73	a-1	a-2	a-3
0.56	b-1	b-2	b-3
0.49	c-1	c-2	c-3

and third groups were aluminum foam sandwich beams made of aluminum foams and aluminum alloy face-sheets. The thicknesses of face-sheet were 0.8 mm and 1.2 mm respectively. Specimens were numbered and shown in Table 2. There were 3 to 5 specimens for each type of AFS, the listed number is the one based on scientific statistics.

There were also three groups of experiments had been performed to study the influence of face-sheet thickness on the mechanical properties of AFS. Specimens were numbered and shown in Table 3. There were also 3 to 5 specimens for each type of AFS, the listed number is the one based on scientific statistics.

3. Results and discussion

The main purpose of this study is to research the influences of foam core density and face-sheet thickness on the mechanical properties, deformation processes and failure modes in aluminum foam sandwiches, especially when the face-sheet thickness is less than 1.5 mm.

As the P-S curves shown in Figs. 2 to 7, curves of load VS displacement of three-point bending tests, there were three stages in P-S curve of AFS. At the first stage the load value briefly increased almost linearly with displacement until it attained the first yielding point, at which local area of the structure attained its yield stress. After the yielding section, the load value increased with the displacement until reached its peak value**.** During bending, the aluminum foam core crushed and compacted, hence, the carrying capacity improved. The bending load increased with the displacement rose until the whole structure cracked or the glued interface failed due to the significant inconsistent deformation between face-sheet and foam core. Finally, the load decreased quickly, the whole structure failed completely.

3.1 Effects of aluminum foam core density on the mechanical properties of AFS

As shown in Fig. 2, it is clear from the line graphs that the carrying capacity increased with the density of foam core in aluminum foam only beams. The peak value of load increased from 0.66405 kN to 0.82717 kN when the foam density increased from 0.49 g/cm^3 to 0.73 g/cm^3. This indicates that the bending strength of pure aluminum foam increases with the density of foam material. The reason for this is that with the increase of density, cell diameter decreased while the wall thickness improved, thus the strength and stiffness of foam enhanced.

For aluminum foam sandwich beams with the face-sheets thickness of 0.8 mm, the influence of foam density on the mechanical properties was the same as what it worked in the foam only beams, the carrying capacity increased with the density of foam core. But the peak value increased by 81% (from 0.83 kN to 4.36 kN in this study) compared with foam only beam. Because when the face-sheet is 0.8 mm, although the whole strength can be improved dramatically by the enhancement of

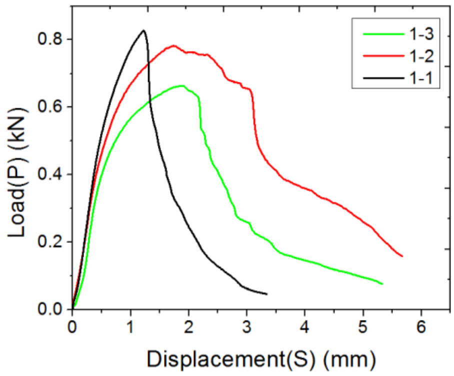

Fig. 2 Curve of S-P of foam only beams

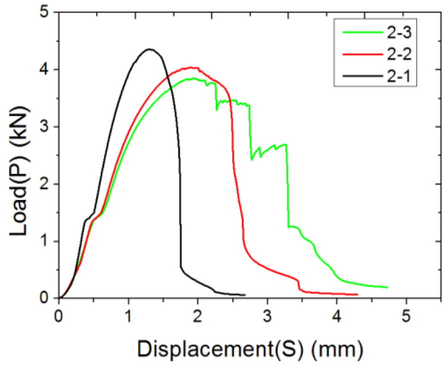

Fig. 3 Curve of S-P of AFS with the face-sheet of 0.8 mm

alloy face-sheet, the variation tendency of strength still depends on the properties of aluminum foam. It means that aluminum foam core plays a major part in sandwich structure when the face-sheet is not thick enough. The result is shown in Fig. 3.

When the thickness of face-sheet increased to 1.2 mm, result was different from the first two categories. Fig. 4 shows that when the thickness of face-sheet was 1.2 mm, the bearing capacity of AFS decreased with the increase of foam density, which is opposite to the foam only beams and beams with 0.8 mm face-sheet. It seems unreasonable, since the bearing capacity of foam materials increase with the increase of their density in general. The reason for this is that when the foam core enhanced by the compact metal face-sheet, the holistic mechanical properties are different from the pore foam material. When the face-sheet thickness improved to a considerable value, it plays the main part in AFS as load-carrying structure. Concern this, when the density of foam core decreased, its porosity increased, thus there was more room for deformation. Energy absorbed during the deformation process, and thus the carrying capacity increased. This is also the reason why the energy absorption capacity of AFS goes up with the decrease of core density. This result is consistent with the result of Liu *et al*. 2013.

It can be learned that the bending strength of AFS did not always increase with the increase of foam density. When the face-sheet was very thin (or without face-sheet), the flexural strength of

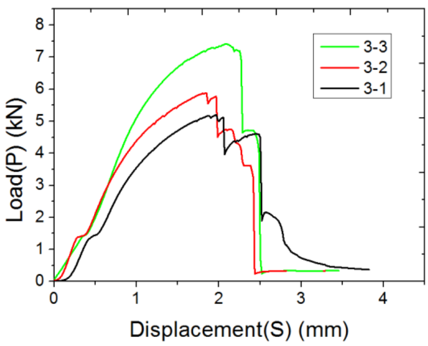

Fig. 4 Curve of S-P of AFS with the face-sheet of 1.2 in thickness mm

Table 4 Peak load, displacement and energy absorption of each specimen

Specimen number	Peak load/ kN	Displacement of Maximum load/ mm	Energy absorption/ kN·mm
1-1	0.82717	1.21875	1.142233
1-2	0.78239	1.73625	1.51520
1-3	0.66405	1.88625	2.77135
2-1	4.36241	1.30250	4.98803
2-2	4.04685	1.90250	7.60654
2-3	3.84937	1.93125	9.62146
3-1	5.20408	1.71750	9.44296
3-2	5.77769	1.97000	10.00267
3-3	7.41442	2.08625	12.71463

Table 5 Peak load, displacement and energy absorption of each specimen

Specimen number	Peak load /kN	Displacement of Maximum load/ mm	Energy absorption/ kN·mm
a	0.82717	1.21875	1.14223
a-1	4.36241	1.26875	4.98803
a-2	4.40569	1.56875	6.89388
a-3	7.41442	2.08625	12.71463
b	0.78239	1.73625	2.77135
b-1	3.85176	1.28500	7.23570
b-2	4.06778	1.94750	9.62146
b-3	5.20408	1.97000	10.002669
c	0.66405	1.88625	1.51520
c-1	4.04685	1.90250	7.60654
c-2	--	--	--
c-3	5.87677	1.83375	9.44296

AFS increased with foam core density, but when the thickness of face-sheet reached to a considerable value, the flexural strength of AFS rose with the decrease of foam core density. The critical thickness was 1.2 mm in this study. The peak value of bending load and corresponding deflection, according to Figs. 2 to 4, are listed in Table 4. The total energy absorption for each specimen selected was calculated by the follow equation. P refers to load and S refers to displacement

$$W = P \cdot S = \int PdS \tag{1}$$

3.2 Effects of face-sheet thickness on the mechanical properties of AFS

Effect mechanism of face-sheet thickness on the mechanical properties of AFS is much simpler than that of foam core density. The first group, shown in Fig. 5, was AFS with foam core density of 0.73 g/cm^3 and face-sheet thickness of 0.8 mm, 1.0 mm, 1.2 mm respectively. One sample without face-sheet was tested under the same bending condition to make a comparison. Result

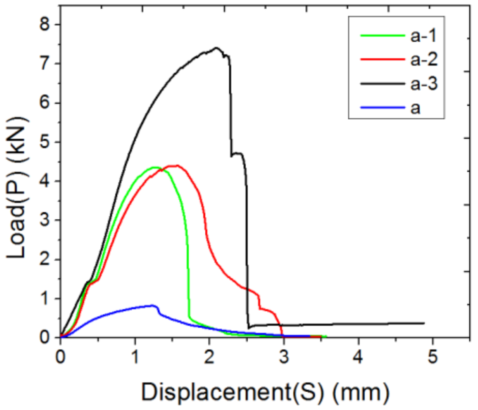

Fig. 5 Curve of S-P of AFS with the aluminum foam density of 0.73 g/cm^3

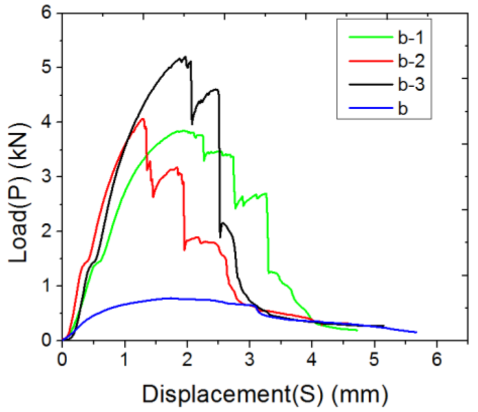

Fig. 6 Curve of S-P of AFS with the aluminum foam density of 0.56 g/cm^3

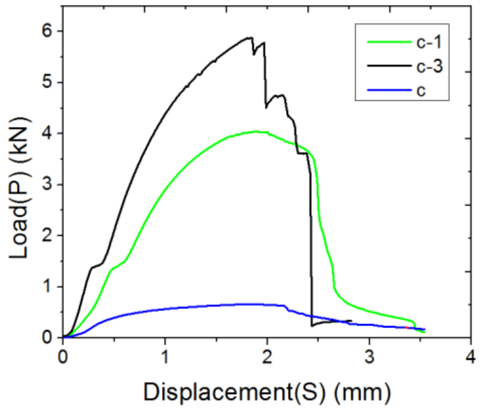

Fig. 7 Curve of S-P of AFS with the aluminum foam density of 0.73 g/cm^3

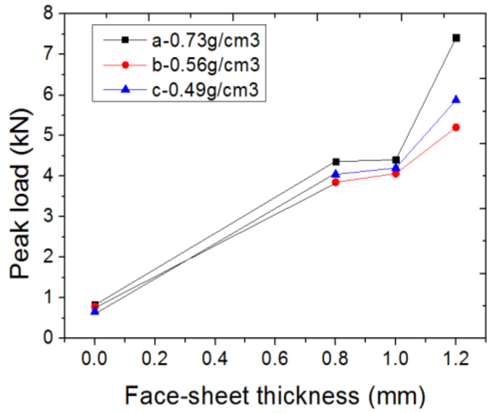

Fig. 8 Variation of peak load with face-sheet thickness

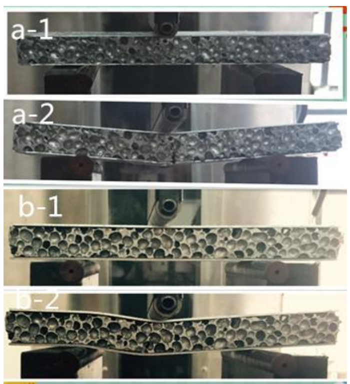

Fig. 9 AFS with 15 mm thick foam core and different face-sheet under three-point bending: (a) thin face-sheet with the value of 0.8 mm; (b) thick face-sheet with the value of 1.2 mm

showed that with the increase of face-sheet thickness, the peak value of load improved significantly, especially when the thickness increased to 1.2 mm. Same results can be gained from the second and third groups as shown in Figs. 6 and 7. Their corresponding values are listed in Table 5. This indicated that the bending strength of AFS increased with its thickness of face-sheet within limits, which is consistent with the result of Zu *et al*. 2013. Although the face-sheet used in their study was steel, the reinforcement mechanism is the same.

It is clear from Fig. 8 that the face-sheet can enhance the bending strength of aluminum foam dramatically. But there still are something interesting can be found. When the face-sheet thickness increased from 0.8 mm to 1.0 mm, the peak load increased slightly (from 4.36 kN to 4.41 kN). But when the thickness increased from 1.0 mm to 1.2 mm, the peak load increased markedly from 4.41 kN to 7.41 kN. Even though the thickness increment was the same, the peak-load value increment was totally different. This indicated that there may be an optimal face-sheet thickness for AFS to obtain a relatively high bending strength. This is a problem need to be noticed and further study is worth doing on it.

3.3 Deformation and failure mode of AFS

On one hand, the P-S curves changing trend of AFS specimens were nearly all the same, but the deformation and failure mode were different. On the other hand, deformation and failure mode were corresponding to P-S curves.

As shown in Fig. 9, there were two deformation behaviors during the experiments: symmetrical deformation (a-1 and a-2) and unsymmetrical deformation (b-1 and b-2). This is corresponding with the schematics of core yield: (a) Mode A; (b) Mode B in (Mohan *et al*. 2005). When face-sheet thickness was 0.8 mm, the integrality of the whole structure was better than that with 1.2 mm, the plastic hinges were at around of the loading points, thus the whole structure deformed symmetrically. When the face-sheet thickness rose to 1.2 mm, the face-sheets has enough strength and stiffness to resist the bending load, thus the load dispersed in foam core and transmitted from the bottom face-sheet to the top face-sheet, and thus the plastic hinges were located at the loading points and supporting points, a specimen failed in this mode was shown in Fig. 9(b). The deformation process in the present study is simpler than the other research (Liu *et al*. 2013). Because in this study the matrix material of aluminum foam is 7050 aluminum alloy, but not pure

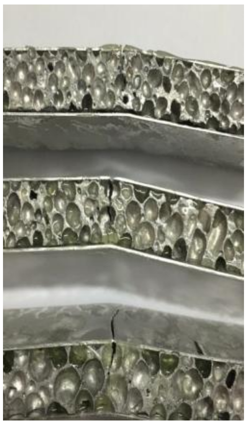

Fig. 10 Failure mode I

Fig. 11 Failure mode II

Fig. 12 Failure mode III

aluminum. Aluminum alloy is harder than pure aluminum and thus there is no noticeable sunken place at the indenter and support points. The whole structure failed with a crisp voice.It is well consistent with the results of Wang *et al*. 2016.

There were three failure modes in this study. Both cracks of core and bottom face-sheet (Failure mode I, Fig. 10), crack of foam core (Failure mode II, Fig. 11) and failure of the adhesive interface (Failure mode III, Fig. 12). This is also corresponding with the result in lecture (Wang *et al*. 2016). For AFS reinforced with thin aluminum alloy face-sheet, the strength and stiffness of core and face-sheet matched well. Due to this reason, the loading capacities of face-sheet and foam core of AFS with face-sheet thickness of 0.8 mm are proportionable, and thus deformed together under loading and failed by failure mode I almost (except some un-perfect adhesive specimens). The bottom face-sheet and core were under tensile stress and shear stress. With the increase of the displacement, the bottom face-sheet and core cracked. The cracks extended gradually until the whole structure failed. For AFS with thick aluminum alloy face-sheet, failure mode was different from thin one absolutely. The thick panel has high strength to resist the bending load and thus some specimens were failed by failure mode II, the increase of displacement resulted in local crackin foam core and the crack ran through thickness direction of the whole sandwich core. After unloaded, the bottom sheet peeled off from the core. In this mode, the bottom face-sheet did not crack for its high strength and stiffness. Meanwhile, the others failed by failure mode III, the top sheet or the bottom sheet desquamated from the foam core due to the weak adhesion. This is a common failure mode in sticky AFS and expected to be improved.

4. Conclusions

Influence of foam core density and face-sheet thickness on the mechanical properties and failure mode in aluminum foam sandwich were investigated under three-point bending condition. Deformation and failure mode were discussed in this study. The main conclusions can be drawn as follows.

- When face-sheet was less than 1.0 mm, the flexural strength of AFS under three-point bending conditions increased with foam core density. When face-sheet was 1.2 mm, the flexural strength of AFS increased with the decrease of foam core density. The critical thickness was 1.2 mm in this study.
- With the increase of face-sheet thickness, the flexural strength of AFS improved dramatically, especially when the thickness increases to a considerable value (1.2 mm in this study).
- There exists an optimal value of face-sheet thickness, thus it is necessary to make an appropriate thickness ratio of face-sheet to core to attain the relatively high bending strength.
- Three failure modes appeared in this study. When the face-sheet was 0.8 mm, AFS failed by Failure mode I, both the foam core and bottom sheet cracked. When the face-sheet was 1.0 mm or 1.2 mm, AFS failed by Failure mode II or III, foam core failed by shear damage or the top sheet or the bottom sheet debonded from the foam core.

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