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Diffusion bonding in fabrication of aluminum foam sandwich panels

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ABSTRACT

This work describes a detailed investigation on fabrication of mild steel-Al foam core sandwich panels (AFS) by vacuum free diffusion bonding method. The foamable AlMg1/SiC_p-based precursor was prepared by powder metallurgy method. In order to prevent the surface oxidation and to facilitate the bonding process, the mild steel sheets were aluminized by hot dipping technique. A series of experiments were completed at various processing parameters for preliminarily evaluating the joint quality and the foamability of the precursor. The distribution characteristics of the SiC_p particles at the bond line was particularly investigated and discussed. The results have shown that a pre-bonding of the steel/precursor was required for the formation of high quality joint between cover sheets and aluminum foam core. Besides, both the fabrication of aluminum foam core and the bonding of the aluminum foam to the cover sheets were achieved simultaneously. An approach for fabricating AFS panels with steel as cover sheet was establish, and an simple model of the diffusion bonding mechanism for the formation of metallurgical bonding interface was proposed. The obtained results may have particularly importance on applications of AFS panels that need firmly bonded joints.

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1. Introduction

Aluminum foam sandwich (AFS) panel is a class of advanced material basing on the conjunction of aluminum foam core and two dense metal cover sheets (Fe, Al or Ti alloy, etc.). The outer cover sheets with good stability and elasticity can not only seal the foam, but also provide enough mechanical properties effectively (Seeliger, 2002). Aluminum foam in AFS panel serves as damping spacer because of the high-energy absorption capacity. A properly designed AFS panels can optimize the mechanical and functional properties much more efficiently; in particular they have good inflammable, heat resistance, excellent vibration damping and high flexural rigidity, etc. (Banhart, 2001; Banhart and Seeliger, 2012). Due to the excellent mechanical and physical performances compared with aluminum foams, AFS panels have more promising application prospects, for example, the possibilities for making lightweight structure components in aerospace (Schwingel et al., 2007), automotive (Ashby et al., 2000; Banhart, 2005), and shipbuilding industry (Crupi et al., 2013).

The joining is one of the most fundamental and tough issues owing to the special structure of aluminum foam. A good adhesion between the cover sheets and the foam core is of great importance for the potentially successful application of AFS panels. Obviously, it is necessary to obtain adhesive forces above the strength of the aluminum foam. Neugebauer et al. (2007) showed that the mechanical properties of AFS panel largely depended on the characteristics of Al foam core and the metal cover sheets as well as the joint quality. Several available methods for manufacturing AFS panels have been proposed based on adhesive bonding and metallurgical bonding. The most obvious and straightforward approach, adhesive bonding, is conducted by combining of the pre-fabricated foam core with cover sheets directly using polymeric adhesive. Associated with the adhesive, this approach has certain problems of low strength, additional mass, difficult recycling and not feasible at high temperature, etc. In order to overcome these disadvantages, one is tempted to investigate a preferable strategy to manufacture AFS that the foam core is metallurgically bonded to the cover sheets. A method for manufacturing metallurgically bonded AFS was primarily developed and improved in Fraunhofer-Institute (Baumeister et al., 1994). In this process, a foamable precursor and two dense cover sheets on both sides were clad-bonded, and then it was foamed to be AFS panel by heat treatment. This approach had been brought to a level of sophistication to allow for manufacturing AFS panels of satisfactory quality. In recent years, Nabavi and Khaki (2010) proposed a new technology via self-propagating high temperature synthesis (SHS). In this way, the Al cover sheet was bonded

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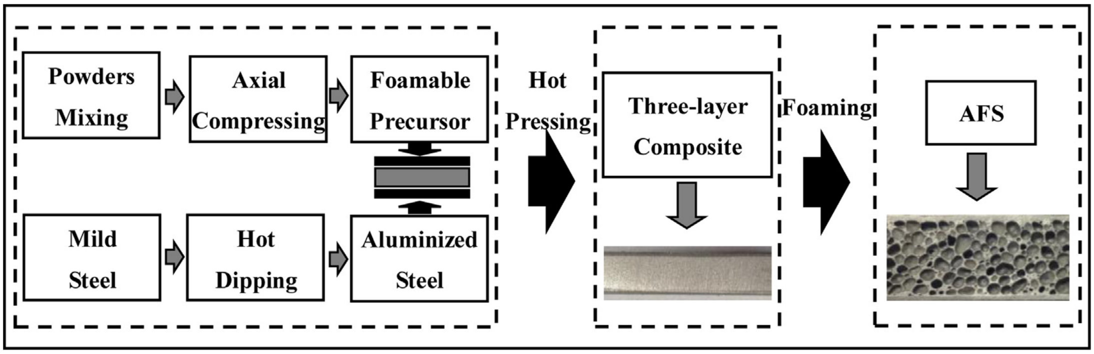

Fig. 1. Schematic illustration of process of fabricating AFS panels by diffusion bonding method.

to aluminum foam core by the melting interface which was caused by the generated heat from the SHS exothermic reaction. But this method had a certain limitation. Since the SHS reaction took place in the foam core/cover sheets, the foam porosity should be low to provide enough surface area for occurrence of the SHS reaction. Hangai et al. (2014) provided an alternative processing route that both the fabrication of the Al–Si–Cu alloy foamable precursor and welding between the precursor and Al alloy plates were simultaneously achieved by friction stir welding (FSW). However, this method was applicable only to parts with certain shapes (preferably with round cross section) and which also had to be machined to provide conical ends. Banhart and Seeliger (2008) reviewed the various processing steps of AFS panels and the metallurgical processes during foaming. They pointed out that a low cost and simple process of manufacturing AFS panels should be developed to widen the range of applications.

Diffusion bonding, as a type of simple joining, demonstrates its potential in the joining of similar and dissimilar metals, alloys, non-metals. Conventional diffusion bonding of steel and Al alloy involved a high vacuum system to maintain clean surfaces. It put a limit on the size of the component and required complicated equipments to improve reliability, as pointed out by Lee et al. (1999). In this paper, vacuum free diffusion bonding for manufacturing AFS panels via hot pressing has been introduced and investigated to facilitate the manufacture process. Focus was placed on the investigation of the formation and evolution of the joints in the fabrication process. Furthermore, a simple analytical model was introduced and discussed to illustrate the bonding process, and to provide an explanation of the diffusion bonding mechanism. The authors intend to attribute to obtain a detailed understanding involved and consequently to optimize further the diffusion bonding process for manufacturing AFS panels.

2. Experimental procedures

The major process in fabrication of AFS panels is illustrated in Fig. 1. By powder metallurgy technique, the aluminum foams were produced using Al, Mg, TiH_2 and SiC powders with purities of 99.7%, 99.0%, 99.0% and 99.0%, and with particle sizes all less than 47 μm. To delay the decomposition range to higher temperature, the blowing agent TiH_2 was heat-treated at 500 °C for 2 h in the oxygen atmosphere according to the principle outlined by Matijasevic et al. (2006) and Luo et al. (2015). The SiC_p powder (mean size 10 μm) was used as the reinforcement particles to relieve the drainage and coalescence of the aluminum foam. The Al powder was firstly mixed with 1% Mg, 0.8% TiH_2 and 8% SiC_p powder in a tumbling mixer. Then, the foamable precursor was fabricated by uniaxial compaction of the mixtures in a stainless steel die by applying a pressure of 400 MPa for 600 s, reaching a relative density higher than 98%.

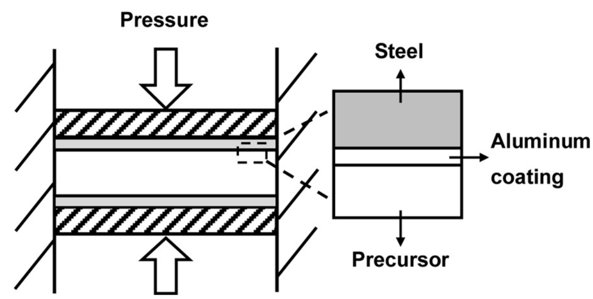

Fig. 2. Illustration of the hot pressing experiments on the aluminized steel and foamable precursor.

Aluminizing treatment is able to prevent the steel from oxidizing successfully. Diffusion bonding of similar metals is much easier to be realized than that of dissimilar metals. The 1 mm thick steel cover sheets were hot dipped by immersing it into molten commercial grade pure Al bath (purity 99.7%) at 720 °C for 180 s, then quenched to room temperature by water. Subsequently, the freshly grinded aluminized steels and foamable precursor were cleaned with acetone by ultrasonic-cleaning to remove the surface contaminants. Fig. 2 depicts the schematic illustration of the hot pressing experiments. The starting material of AFS panel, a three-layer structure composed of two steel plates on both sides and a foamable precursor was prepared in size of 30 mm × 15 mm × 5 mm. The variables used are as follows:

1. Hot pressing temperature: 490, 510, 530, 550 °C.
2. Holding time: 300, 600, 900, 1200 s.
3. Applied pressure: 6, 8 MPa.

The prepared three-layer composites were foamed to be AFS panels in a pre-heated electric resistance furnace at a temperature of 720 °C. After the samples were heated and held at this temperature for a period of time, they were removed and cooled to room temperature by forced air. The foamability is evaluated by the volume expansion factor E which can be approximately described by the following equation.

$$E = \frac{(V - V_0)}{V_0} \quad (1)$$

where: V- volume of the aluminum foam. V_0- volume of the foamable precursor.

The AFS panels were cross-sectioned perpendicular to the bonding direction using a electrical-discharge cutting machine for examination. The samples were abraded and polished using standard polishing techniques, then degreased with acetone and cleaned with ethanol by ultrasonic cleaning. The microstructures and morphologies of the interfaces were characterized and ana-

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