Aluminum Foam Sandwich

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The aluminum foam sandwich (AFS), a typical AFCS, is composed of external solid panels and an internal porous aluminum foam core. According to the service conditions and manufacturing method, titanium, steel, aluminum, wood, ceramic, carbon fiber, and other materials can serve as the above-mentioned solid panels.

Keywords: porous metals ; aluminum foam composite structures

1. Adhesive Bonding Method

Adhesive bonding is the most direct and effective method to combine the panels and the aluminum foam core, and this method also has the advantages of high efficiency and low cost. The primary preparation process includes the following steps. Firstly, the bonding surfaces of solid panels and aluminum foam core surfaces are polished using sandpaper, ensuring superficial roughness. Secondly, the preprocessed panels and aluminum foam core are cleaned with ethanol or acetone to remove oil and impurities. Thirdly, an adhesive is applied to the preprocessed surface, and these parts are combined under certain temperatures and pressures [1].

From the perspective of the bonding surfaces, a porous structure causes a rugged bonding surface, so only the skeleton area can contact a solid panel during an appropriate pressure, and the effective bonding surface is insufficient. Concave pore surfaces are difficult to clean, and grease, scraps, and cutting liquid adhere to the pore's inner surface, weakening the bonding strength. To improve the bonding strength of the AFS, many scholars have adopted various modification methods to treat both the panel and aluminum foam core surfaces, and a high-temperature adhesive method has also been employed. For example, nitrogen plasma has been used to pretreat aluminum foam and aluminum plates to increase the surface hydrophilicity of the aluminum and the adhesive [2]. Surface modification methods, such as silane treatment and silane treatment combined with a polypropylene base film addition, have been used to bond fiber–metal laminates and Al foam. An AFS with aluminum alloy sheets fabricated using an improved bonding process with an epoxy adhesive [3] showed excellent bonding strength, and the whole AFS presented superior compression and energy absorption properties [4]. Replacing traditional adhesives with high-temperature adhesives [5] can improve the high-temperature mechanical properties of the AFS. AFSs prepared directly with carbon fiber/epoxy composite laminates as the upper and lower panels also have certain bonding strengths [6][7].

Adhesive technology only influences the bonding strength between the core and panels, the internal pore structures of the AFS are controlled by the aluminum foam core, which is formed by slicing the aluminum foam bulk. In other words, the pore morphology of the AFS is mainly related to the aluminum foam bulk preparation method. To date, aluminum foam cores have been mainly prepared by employing the melt foaming method.

In conclusion, the internal aluminum foam core contributes to the functional properties, the external solid panels bear the main loading, and the bonding area acts as a middle layer transferred load. Therefore, many scholars have exhausted improving adhesive technology to improve the bonding strength, and the most widely used adhesives are AB adhesives, polycarbonate resin, and epoxy resin. Despite this, due to the properties of the polymer adhesive itself, melt and metamorphism limits the adhesive's working conditions. Although some certain high-temperature adhesives can adapt to short-term high-temperature environments, the aging phenomenon exacerbates inevitably during long-term use, and their application is limited [8][9].

2. Welding Method

Welding, known as an industrial tailor, has been widely used to join metal materials; in this regard, welding can also be applied to joint aluminum foam core and metal panels for fabricating an AFS. The main welding methods for AFSs include brazing, diffusion welding, and friction stir welding [10][11][12].

2.1. Brazing

Solders are necessary for braze welding, which are molten and fill the weld area [13][14]. Under certain welding conditions, the brazing method can achieve the metallurgical bonding of an aluminum foam core and sheet metal. The main technological processes are similar to the adhesive bonding method. Firstly, both the core and panels are cleaned to remove the oxide layer and grease. Then, solders are inlaid on one side of the panel and flux aqueous solution is sprayed. Finally, the combined core and panels are placed in a brazing furnace filled with nitrogen [15][16].

The holding temperature and time during the brazing process are key factors in the joint quality. Experimental results show that if the brazing time is too long many Al/Fe intermetallic compounds are produced in the joint. These brittle phases reduce the shear strength of the joint, and the mechanical properties of the AFS materials are affected [17][18]. Additionally, improving the solder’s wetting and diffusion behavior can effectively increase the bonding strength between the aluminum foam and the panels, achieving joints with high bending strength [19]. Based on the above discussion, an AFS prepared with zinc-based solders has shown good bending properties [16].

Metallurgical combination is generated when a suited solder is added during high-temperature brazing for fabricating an AFS. Simultaneously, some defects appear in the brazing joints if the brazing temperature is high. Oxide layers generated on the bonding surface under high temperature, coupled with the changed wettability because of a covered oxide layer, are the key factor. In general, reducing the oxidation of joints can improve brazing quality. Based on the above discussion, Wan et al. [20] adopted the slag-free brazing method to prepare an AFS. The experimental results show that the aluminum foam core and panel produce metallurgical bonding without stratification.

All in all, the temperature, time, solder, cleaning, and heating method are the main control parameters for brazing AFSs, and many scholars have devoted energy to improving bonding strength between the panel and the aluminum foam core. Due to the joint quality and low cost, the brazing method for AFS fabrication presents a potential industrial application. Brazing is widely used in industry and is suitable for welding components that are precise, complex, and composed of different materials, such as honeycomb structural plates, turbine blades, carbide cutting tools, and printed circuit boards.

2.2. Diffusion Welding

Diffusion welding is performed at a certain temperature and pressure, with atoms diffusing at the interface and forming a strong joint. A vacuum or a protective atmosphere is necessary. Microplastic deformation (solid-phase diffusion) or the micro-liquid of the welding surface (liquid-phase diffusion) promotes atomic diffusion. In preparing the AFS, atoms are diffused between the panel and the core to form metallurgical connections [21]. During the diffusion welding process, microplastic deformation occurs first at the interface under pressure, and, as a result, the contact area gradually expands. Atom interdiffusion at the expanded contact area forms a bonding area. With increased holding time, atomic diffusion gradually develops to the deep layer, generating intermetallic compounds and achieving reliable joints.

For preparing an AFS, transient liquid diffusion welding is more suitable compared with solid-phase diffusion, because the latter method requires high surface quality and a long holding time [22]. Experimental results have showed that the fatigue life of an AFS prepared by ultrasound-assisted liquid diffusion welding is much longer than that prepared by the adhesive bonding method [23]. Open-cell AFS has been successfully fabricated using the vibration-assisted liquid bonding method; shear tests showed that vibration could significantly improve the bonding quality [24]. Despite this, solid-phase diffusion welding for preparing an AFS has its advantages, such as good bonding strength and it does not melt metal [25].

2.3. Friction Stir Welding

Friction stir welding [26], regarded as a solid-state bonding technology, has been used widely in welding dissimilar materials [27]. During friction stir welding, the high-speed rotated stirring head is started, and then the cylindrical stirring needle is squeezed into the combined plates until the shaft shoulder contacts the panel [28]. Mechanical energy from the stirring needle transfers into the thermal energy of the material, and powders in the combined plate cause plastic rheology and mixing. Different from other methods, both the foaming process of the core and the combining of the panel and the core are implemented at the same time during friction stir welding [29].

Research has shown fabricated aluminum foam complex-shaped parts with a uniform porous structure when the weld spacing, speed, and rotational speed were 3 mm, 50 mm/min, and 2000 r/min [30], respectively. An AFS prepared by friction stir welding presented excellent bending strength, impact protection performance, sound absorption, and reduction performance [31]. Hangai [32] prepared an aluminum foam/dense steel composite by friction stir welding; the mixing of the foaming agent and aluminum powders and the bonding between the aluminum precursor and steel were achieved simultaneously. Although the precursors formed a brittle intermetallic compound layer at the interface after heat treatment, these intermetallic compounds had a higher strength than that of the aluminum foam core. There are two typical reasons for the high bending strength of an AFS prepared by friction stir welding [33]: (i) the connection between the panels and the aluminum foam core is achieved through the plasticized metal flow without introducing new materials and (ii) friction stir welding refines the grain of the panel, leading to an improvement in the panel.

From the perspective of joining technology, friction stir welding can also be used for welding AFSs. Due to high-speed rotation and movement of the stirring head, several small pores were generated at the core and panel mixing area [29]. For internal pore structures, the average thickness of the cell wall for the bonding areas was larger than that of the core material, and an obvious welding interface can be observed. Because of the random foaming, a few large inhomogeneous pores appeared after the agglomeration of foamable particles during the mixing process [34]. Welding marks can be observed on the outer surface of the panels.

3. Powder Metallurgy Method

The main raw materials for fabricating an AFS using the powder metallurgy method are aluminum alloy powders, TiH_2 particles, and metal panels. Before the foaming process, aluminum powders and TiH_2 particles are mixed, and then the mixture is compacted into a foamable precursor with bilateral metal panels. In general, the key factor for fabricating an AFS is the bonding strength between the core and the panels, as well as the densification of the foamable precursor. The densification of the powder is mainly achieved by pressing, rolling, and wrapping rolling. At the same time, cold pressing or hot pressing is used, or two other kinds of technology are used simultaneously for powder preparation. In general, hot pressing is the most widely used method, as the main bonding mechanism of an AFS prepared by powder metallurgy is thermal diffusion [35].

The preparation of an AFS using powder metallurgy is limited by the densification of the precursor and the quality of the internal pore structure, also this method has the disadvantages of a high preparation cost and a small product size. To overcome these disadvantages, scholars have prepared AFSs by changing the pressing method and carrying out a lot of research [36][37][38].

3.1. Cold- and Hot-Pressing Powder Metallurgy Method

The cold- and hot-pressing powder metallurgy method is a widely used method for fabricating an AFS. The main processes [39] include mixing powder, cold pressing, hot pressing, and foaming. Appropriately extending the mixing time can improve the uniformity of the achieved AFS. The purpose of cold pressing is to form a bulk material from powders to transfer it from one mold to another, because the molds for cold and hot pressing are sometimes different. Hot pressing is a critical process to achieve a dense precursor core and a good bonding strength between the precursor core and the panels. The adjustable parameters are pressure, time, and temperature. Foaming is the last step, in which the density and pore size of the core can be controlled by adjusting the foaming time and temperature. Additionally, this process improves the bonding strength between the precursor core and the panels.

Results have shown that Al, Mg, and TiH_2 with a purity of 99.7%, 99.0%, and 99.0%, respectively, can be used to produce aluminum foams by powder metallurgy technology. About a 400% expansion phenomenon was observed when the hot-pressing temperature and pressure were 490 °C and 8 MPa, respectively [35]. An excellent bonding area between the core and the panels with a high metallurgical quality [35] was obtained in this case. Ding [40] introduced a new method for preparing foamable AFS precursors by hot pressing. An AlMg4Si8 alloy was formed by mixing Al, AlMg50, and Si powders, and then 0.5 wt% TiH_2 was added for foaming. It was found that the suitable preparation conditions were cold pressing and then hot pressing at 450 °C [37][41]. A tight metallurgical bonding layer between the panels and the core was generated as atom mutual diffusion was promoted under high temperatures. For example, iron from a steel panel was diffused with aluminum through the interface and formed FeAl3 [42], and titanium panels formed intermetallic compounds of TiAl3 and Ti2Al5 [43]. From another perspective, plastic deformation caused by hot pressing can also reinforce the bonding strength [44].

To improve the internal pore structures, the foaming technology of powder metallurgy was exhausted and studied [45]. By investigating the evolution process and dynamic mechanism of foamed samples during the foaming expansion process, the foaming process was divided into three stages. Stage I was the pore-forming stage, with TiH_2 particles decomposing, and the generated gas pressure gradually caused some small pores. Stage II was characterized by pore growth and pore coalescence. During Stage III, the sample expansion stopped and started to shrink. Hence, controlling the foaming stage is key for fabricating high-quality pore structures.

3.2. Rolling Powder Metallurgy Method

The densification process of this type of powder metallurgy method is rolling [46]; in this process, the panels and the mixed powders are compacted by extrusion and compound rolling to obtain a foamable precursor. Rolling is a continuous process, so the rolling powder metallurgy method is suitable for industrial production. To improve the densification of the precursor, the rolling process is usually implemented under high temperatures [47], and then the prepared precursor is heated in a furnace to an appropriate temperature for foaming. With the increased temperature, the precursor transforms to a semi-melting state, and the decomposition of TiH_2 occurs at the same time; as a result, bubbles are generated. Simultaneously, atom diffusion occurs between the panel and the core, forming intermetallic compounds and achieving an ideal metallurgical bonding state.

Experimental results have verified that the rolling powder metallurgy method for preparing an AFS can obtain a higher densification of the core and present a better interface bonding strength [48] compared with the traditional hot-pressing method. Nevertheless, there are also some disadvantages in the rolling process. Flow and loss of core powder causes an uneven rolling force on samples, stress concentration is easily caused at the high-density area of the powder, and, as a result, cracks are generated. In addition, some micro-cavities can be observed in the low-density area. Large-sized TiH_2 particles can cause some micro-cracks in the surrounding structure [49][50].

The rolling powder metallurgy method can continuously realize the preparation of large-sized AFSs, the prepared precursor has high densification, and there is a high bonding strength between the panels and the core. The agglomeration of foaming agents can be effectively solved by controlling the foaming temperature, rolling pressure, foaming agent content, and powder mixing process.

3.3. Jacketing Rolling Powder Metallurgy Method

To solve the powder loss problem, the jacketing rolling powder metallurgy method was put forward based on the rolling powder metallurgy method. An AFS prepared using the jacketing rolling powder metallurgy method has the characteristics of good powder uniformity and high shape accuracy [51]. Jacketing rolling [52] can effectively improve the density of the precursor, and the powder utilization rate is close to 100%.

Experimental results have verified that an AFS prepared by the jacketing rolling method has excellent metallurgical bonding between the core and the panels and can withstand a higher bending load [53]. Song [54] successfully prepared an AFS sheet using air-atomized 99.0 wt% AlSi12 powders, 1.0 wt% Mg powder, and 1.0 wt% TiH_2 powder as raw materials when employing the jacketing rolling method; the results illustrated that jacketing rolling can effectively prevent the crack propagation of the panel. Sun [55] studied the influence of the rolling temperature on the preparation of AFS precursors by the jacketing rolling method; the experimental results showed that precursors with excellent density and an excellent bonding interface were prepared at the rolling temperature of 400 °C. Wang [56] introduced a melting process of an AFS powder block based on the jacketing rolling method; the prepared AFS appeared to have an excellent cellular structure and excellent mechanical properties when the optimal reduction rate was 80%, the relative density was more than 0.98, and the material utilization rate was close to 70%.

3.4. Other Methods

Based on the powder metallurgy method, Kitazono [57] proposed a novel practical technique for fabricating closed-cell aluminum foam plates using cumulative roll welding (ARB). Hosseini [58] prepared an AFS using continuous annealing and roller compression (CAR). These two methods realized the preparation of the AFS and the main routes for ARB and CAR were roughly the same.

Although ARB and CAR can be used for fabricating large-sized AFSs, the uniform dispersion of the foaming agent between each strip is a problem, leading to AFS samples having a deficient pore structure, such as large pores and extremely uneven pore distribution [57][58]. Adding 0.75 wt% SiC particles to the foamable precursor can reduce the size of the pores and the uniformity and roundness of the pore structure can also be improved; however, the smooth surface of the aluminum foam plate becomes degraded [58].

4. Melt Foaming Method

Melt foaming is the most widely used method for making bulk aluminum foams. By dispersing a TiH2 foaming agent into the thickened aluminum solution, aluminum foam is prepared by rotating the blades at high speed and combining aluminum foam with panels in different ways for a prepared AFS. On this basis, it is mainly divided into two routes.

Compared with the powder metallurgy and welding methods, the panels and the aluminum foam core of the AFS using the melt foaming method are joined by transient liquid diffusion. Little metallurgical bonding is formed in the bonding area, so this method can effectively solve the sample size problem. Different from the secondary processing of the powder metallurgy method, it is expected to realize the direct formation of an AFS and presents great potential for application in industrial production.

A melt-foaming-fabricated AFS showed a metallurgical bonding layer at the interface between the core and the panels, and the thickness of the bonding layer increased with an increased holding time. Ternary phase $Al_{20}CaTi_2$ and binary phase Al_2Ti were detected in this bonding layer [59]. Regarding the two-step foaming method, a new slow-released foaming agent appeared to have excellent performance, as it presented a low loss rate in the early stage and a high foaming efficiency in the late stage [60]. The melt foaming method for fabricating an AFS has the characteristics of a short process, relatively uniform pore structures, sufficient bonding strength, and less limits in the specimen size. Therefore, a melt-foaming-fabricated AFS has great potential and will be competitive in the future.

All in all, the external panels greatly improve the bearing capacities of single aluminum foam, and the internal aluminum foam core has damping shock absorption, sound absorption, noise reduction, heat insulation, electromagnetic shielding, and other excellent performances [61][62][63]. Hence, AFS structures appear to have great potential in aerospace, marine and automobile transport, rail transport, and other fields, and the AFS structure is also one of the materials widely studied by many countries [64][65].

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