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Interfacial behavior and mechanical properties of aluminum foam joint fabricated by surface self-abrasion fluxless soldering

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A B S T R A C T

Fluxless soldering with surface self-abrasion has been developed for joining aluminum foams with metallic bonding. The effect of the self-abrasion on the wettability of molten solder alloy and mechanical properties is determined by microstructural observation, tension and compression tests. No apparent macroscopic deformation and collapse of foam structure are observed adjacent to the joint interface. The average tensile strength of the joints is about 14% higher than that of aluminum foam, and the compressive strength can reach 200% of that of aluminum foam. The deformation mechanisms and energy absorbing characteristics of aluminum foam and the joint are investigated. The aluminum foam joint fails primarily by bending, crushing, and compaction of cell walls and cracking of the solder seam. The interdiffusion process is explained based on thermodynamic equations.

1. Introduction

Aluminum foam, due to its high porosity, is characterized by a number of unique properties, such as low density and mechanical energy absorption capabilities [1]. It has been drawing much attention in structural applications where weight reduction and energy absorption are needed such as in the automotive, aerospace and railway industries [1–4]. Currently, aluminum foams can be fabricated by many different methods, such as solid–gas eutectic solidification [5], high pressure casting method [6], powder metallurgy method [7], and melt-foaming method [8]. In terms of these existing techniques, it is still difficult to attain large aluminum foam products and complicated structures, which is a key obstacle in expanding real applications of aluminum foams. To ensure that metal foams can meet industrial demands, the above-mentioned applications require reliable and durable joining methods [9]. Moreover, processes that allow the conservation of the foam specific properties are especially important [10].

Joining by adhesives has been used in most metal foam structures. Though the adhesive bonding process is superior for low temperature applications, the expansion to high temperature region is limited [11]. Owing to high porosity content of aluminum foam, the considerable structural deterioration of the foams is unavoidable when conventional fusion welding processes, such as tungsten inert gas (TIG) and laser beam welding, are used [10,12]. Additionally, the solid-state diffusion bonding is proposed to join metal foam [11]. This technique is considered for joining stainless steel foams as the bonding temperatures are always below and normally about 70–90% of melting point [13]. Diffusion bonding process typically requires large compressive stress to break up oxide layers and to contact the surfaces closely enough. However, aluminum foams will easily deform under such a large stress. Welding techniques with pressure, such as ultrasonic torsion welding and pressure welding, will also cause unacceptable deformation [14,15]. The collapse and deformation of foam structure will have significantly negative effects on mechanical properties of aluminum foams [16,17]. Therefore, two main conditions should be preferably considered when choosing candidate method for joining aluminum foams. On the one hand, the bonding temperature should be below melting point of metal foam to prevent any structural deterioration. On the other hand, the bonding process should be associated with the formation of liquid phase at the joint interface so that high pressure can be eliminated.

The possible methods based on brazing and soldering have been investigated [18–20]. Ashby et al. [18] indicate that the removal of oxide layers in case of fluxless soldering aluminum foams may be problematic. They also claim that soldering without the use of flux requires at least partial removal of oxide layers to allow a direct

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contact of molten solder alloy with foam surface. Nowacki et al. [9] suggest that a feasible soldering method of aluminum foams is soldering without flux. Sendliakova et al. [19] investigate tensile strengths of foam specimens soldered with Sn90Zn alloy and claim that the possible way of removing oxide layers is either rubbing the surface with appropriate tool under molten metal or using a flux. The proper direction toward soldering optimization of aluminum foam seems to find out a process requiring low operating temperature, thereby allowing aluminum foam to maintain its full strength, and providing a joint the strength of which exceeds that of aluminum foam. However, there is still much work needed to determine suitable solder alloy and proper methods to remove oxide layer, which greatly impedes obtaining a reliable joint. Recently, fluxless soldering with surface abrasion assisted by a needle has been developed by Huang et al. [15]. Assisting with mechanical abrasion, fluxless soldering using a Zn-based alloy is proven suitable for joining aluminum foams [15]. Consequently, it is necessary to develop more available and efficient methods for joining metal foam.

The aim of this paper is to develop a novel and efficient method for joining aluminum foam and provide an insight into tensile property, the deformation and energy absorption performance of the joint. Microstructure observation and thermodynamic analysis are conducted to investigate the weld seam.

2. Experimental section

The closed-cell aluminum foam is provided by Southeast University of China. The chemical composition of aluminum foam is Al-1.2 wt.% Ca-1.1 wt.% Ti-0.3 wt.% Zn. The mean cell size is 2–3 mm in sheets. Closed-cell aluminum foam is manufactured by means of powder metallurgical process. The process starts from a powder mixture of aluminum alloy and blowing agent of TiH_2 powder. Then, the compacted material is heat treated near melting range of aluminum alloy. The TiH_2 particles decompose to release hydrogen gas at high temperature and the gas is used to produce a foamed aluminum ingot. The density of aluminum foam used in this study is about 0.30 g/cm^3, which is measured by the direct weighing, and the porosity percentage was approximately 90%. The specimens are all taken from same foam block and the selected foam block is cut into dimensions of 60 mm × 60 mm × 20 mm by electric discharge machining, and then rinsed in acetone. A solder alloy of 6.2 wt.% Al, 4.3 wt.% Cu, 1.2 wt.% Mg, 0.8 wt.% Mn, 0.5 wt.% Ag and balance Zn is chosen. Its melting range is in the range of 396–405 °C, which is below melting range of aluminum foam to prevent any structural deterioration [15].

The detail steps and related parameters are summarized as follow. As a heat source, the manual oxygen-propane torch soldering is performed in air condition, and heat treatment temperature is approximately 420 °C. Once solder alloy is melted, it is homogeneously coated on both bonding faces of aluminum foams, as shown in Fig. 1(a), (b) and (f). The aluminum foam is hold by the fixture that is movable to make it back and forth with the average speed of 10 mm/s, as shown in Fig. 1(c). The soldering is performed between aluminum foams, applying a pressure of 2–3 kPa in the normal direction to the joint surface and keeping heating for 2 min.

The microstructure and interface feature of the joints are examined by a scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS). Tension and compression tests are performed to examine mechanical properties of joints using a universal mechanic testing machine (Instron UTM, model 5569) at room temperature. Specimens (80 mm × 10 mm × 10 mm) with a double-edge notch within the joints are prepared for tension test, as shown in Fig. 2(a). The depth of notches is 3 mm, and two specimens are used to conduct tension test. The dimensions of the specimens for compression test are 20 mm × 10 mm × 20 mm, as shown in Fig. 2(b). The specimens are loaded at a constant rate of 0.5 mm/min and 2 mm/min for tension and compression tests, respectively. The orientation of the specimens is perpendicular to bond plane for tension test, and the orientation of the specimens in compression tests is in the direction normal to bond plane. Additionally, in compression tests, the load is removed once the strain reaches 20%. The following formula is related to the under area of strain–stress curve and can be used to calculate the capacity of the energy absorption [4]. The strain and compressive stress are respectively ε and σ in formula (1). Photographs are taken to identify the deformation of the joint.

$$W = \int_{0}^{\varepsilon} \sigma(\varepsilon) d\varepsilon \tag{1}$$

3. Results and discussion

3.1. Macro and microstructures of joints

Fig. 3 shows typical soldering seam of aluminum foam joint made by fluxless soldering with surface self-abrasion. A metallurgical bonding has been formed between aluminum foams without any apparent plastic deformation and collapse of the foam cell adjacent to the joint interface. The original properties of aluminum foam are preserved during the process. The molten soldering alloy does not spread along cell walls, as shown in Fig. 3(b) and (c). This phenomenon can be explained by two main reasons. The first reason is that the oxide layer on cell wall significantly impedes the spreading of molten solder alloy. The second reason is the negative influence of the gas phase existed in closed foam cell on spreading of molten solder alloy along cell walls. Due to the pressure loading on aluminum foam during soldering, gas phase produce a counteraction to prohibit the spreading of molten solder alloy. The dense, uniform and continuous bonding layers are formed between aluminum foams, which can be seen in Figs. 3(b), (c) and Fig. 4(a). No macroscopic cracks are found in soldering seams. Since the wetting and spreading are decisive prerequisite for forming a continuous seam, such macroscopic overview suggests that good wetting and spreading behaviors occur.

To evaluate the phase contents of interfacial layers, spot EDS analysis is carried out. Three types of phases are identified according to their microstructural morphology and chemical composition in the interface. Each type of phases is marked with A, B and C successively, as shown in Fig. 4(b). The EDS analysis reveals that light gray (A) and dark gray (B) phases are Zn–Al solid solution (66 at% Zn and 33 at% Al) and Al–Zn solid solution (75 at% Al and 23 at% Zn) phases, respectively. The remaining white phases (C) are composed of 93 at% Zn and a pretty small amount of Al (4 at%), as shown in Fig. 4(d). To examine the evidence of the mutual diffusion in detail, the compositions of Al, Si, and Zn elements in the area around the bonded interface is measured by a line-scanning analysis, as shown in Fig. 4(c). The Al and Zn elements are distributed continuously throughout cross-sectioned joint. The fibrous roots, marked in Fig. 4(b), are also a clear manifestation of such interdiffusion. These results suggest that the mutual diffusion is achieved between solder alloy and aluminum foam.

The oxide film has a significantly negative effect on the wettability of molten solder alloy. Almost no molten materials can wet a material covered in a dense oxide layer [20]. During the soldering process, the aluminum foam is hold by the fixture which is movable to make it back and forth on the aluminum foam which is fixed on