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Weld structure of joined aluminium foams with concentrated solar energy

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ABSTRACT

Concentrated solar energy was applied to welded foam plates in non-protective atmosphere. The filler was a pore-generating aluminium–silicon alloy placed between two commercial aluminium foam plates. The heating device provided enough energy to melt and foam the filler. The heat affected surfaces on foam plates and welding mechanisms were correlated with heating conditions. Test plate thickness controlled filler foaming, and two runs were necessary to complete foaming. Weld characterization through tensile tests and microstructural study was performed. The role of the oxide layer on the weld was analyzed and the main welding mechanisms identified: a mechanical form-fit and a metallurgical connection.

1. Introduction

The main characteristic of closed-cell metal foams is their combination of energy absorption and weight. Weight-specific properties of metal foams include lower density than other massive materials. Foam density is usually 25–90% of density of solid materials. Al-foam plates are used on light structures with high strength and are very visually appealing. Aluminium foams have higher strength and non-combustibility than plastic foam. However, large aluminium foam products and complicated structures are difficult to obtain using foam manufacturing techniques, and this difficulty is a key obstacle to expanding future applications of aluminium foams. Both reliable joining techniques and cost-effective processes are required to meet industrial demands. Aluminium foams can be obtained with low joining temperature—through mechanical or glueing methods—as well as high joining temperature—through brazing, soldering or welding. These techniques have been applied to cellular metals to join foams to each other as well as to components made of solid metals.

Aluminium foams from melts are widely used as panels, and conservation of foam-specific properties has led to use of foamable precursor to act as filler in foam welding. Bach et al. (2001) report using a precursor as filler to adapt foam structure to the joining zone between two aluminium foam plates. Expansion of melt from heating the precursor (filler) causes metal to penetrate into base foam pores, a phenomenon also reported by Matthes and Lang (2001). This procedure improves contact between the final foam from the precursor and the base foam or solid base metal when weld between foam and a solid sheet of metal is desired. Furthermore, Haferkamp et al. (2004) reported that a foam structure in the welding zone will allow a lower gradient in mechanical and physical properties throughout foam weld, a condition necessary, for example, in automotive technology. In addition, use of filler material, such as foam precursor, inserted between foams to be joined makes it possible to fill the gap between parts. Also Haferkamp et al. (2004) report that achieving desired joint strength depends on the mechanism for joining foamed precursor (filler) and foam part.

Filler metal must be heated to over 600 °C to be foamed and join parts. Bach et al. (2001) report local methods to join aluminium foams such as inductive, resistance, flame and light heating as the most feasible for similar melting materials. Cambronero et al. (2010) report successful use of solar energy in aluminium foaming and Karalis et al. (2005) in solar concentrated energy AA7075 welding. Advantages of solar energy are treatment of longer surfaces than with laser, high heating rates, low environmental impact and good suitability for materials that absorb radiation on the visible spectrum. Laser beam welding is also feasible for joining sheet materials and aluminium foams (Bernard et al., 2001).

Drawbacks of concentrated solar energy include variation in energy source intensity over time and need to take some variables such as wind speed into account during testing, since beam focus location depends on heliostat movement. As to the joint,

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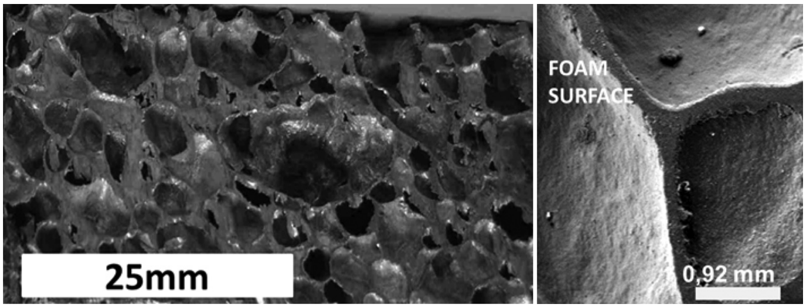

Fig. 1. Aluminium foam plate section to be joined (left) and cell structure (right).

concentrated solar energy can be focused on the welding zone, as occurs with laser, enabling a high temperature gradient and small heat-affected zones and eliminating the need to heat parts to be joined in their entirety, as is required with brazing (Matthes and Lang, 2001).

Metals absorb solar radiation better than laser, which usually uses a wavelength close to 10.6 μm in aluminium foam welding with foamable filler metal (Haferkamp et al., 2004). The characteristics of parts to be joined are also critical in laser welding, making the process more stable on foam-dense sheet material than on foam-foam joints. When aluminium foam is welded to aluminium structures, higher conductivity of dense aluminium in these structures yields more rapid heat transfer from the weld zone than with foam-to-foam welding. Filler rod, sheet metal and paste mixture containing foaming agent or foamable filler have always been tested using gas shielding. Results reported by Haferkamp et al. (2004) show that stable deep penetration occurs when the laser beam is focused on the surface of the sheet metal strip to be used as filler material once it is melted.

In this paper, aluminium–silicon precursor is used as filler during foaming in a solar furnace. The high silicon content of these Al–Si precursors has a positive influence on weldability of the base foam, which has favourable flow behaviour once molten metal is formed during precursor (filler) heating.

2. Experimental procedure

2.1. Materials

Commercial aluminium plate with a thickness of 25 mm obtained by melt route was used as base foam to be joined. Al-foam plates are made of aluminium with approximately 1.5% calcium and a similar amount of foaming agent TiH_2, both added during the melting process (Miyoshi et al., 2000). Once bubbles accumulate due to hydride decomposition, the cooled melt produces pores in a solid aluminium matrix. The density of the aluminium foam (0.2–0.25 g/cm^3) is then only approximately 10–15% that of full aluminium (2.7 g/cm^3).

Foam plates (test plates) close to 75 mm × 75 mm thick were cut using SiC disc cutting without thermal effects, due to water cooling. Foam plate cutting leads, however, to wall cell deformation and partially closing cells. Grinding was thus used to open cells on the surfaces to be joined (Fig. 1). Pore surface was not cleaned mechanically, as in the case of Huang et al. (2012) when soldering was used. Open cells or pores allow better filler expansion on test plates, since pore-generating filler such as foam precursor can adapt better to this porosity when present in the welding zone.

Commercially available precursors in the form of 20 mm × 5 mm and 40 mm × 5 mm extruded bars were used. Precursor bars are AlSi (10–12% Si) alloy with 0.8% TiH_2 as foaming agent. They showed uniform distribution of silicon and foaming agent (TiH_2) in the aluminium matrix. Precursors were cut to be used as filler between two aluminium foam plates and then subjected to acetone surface cleaning.

Precursor foaming is based on decomposition of the foaming agent into a gas when the aluminium matrix melts (Fig. 2). Non-optimized parameters and unavoidable gravitational effects influence the foaming process of PM precursor adversely, as Banhart and Seeliger (2008) report. The heating rate must be as high as possible to prevent formation of gas in a non-melted aluminium matrix, since titanium hydride begins to decompose at temperatures over 450 °C, far below the melting point of aluminium. Low-melting-point aluminium alloys such as Al–Si alloy are used to decrease the gap between the temperature of foaming agent decomposition and the melting point of aluminium.

2.2. Concentrated solar energy heating

Radiant flux, such as concentrated solar or laser flux, which falls on the surface of aluminium precursor or other metal, is partially reflected, partially transmitted and partially absorbed by precursor. Clean, polished aluminium is advantageous when absorption of sun radiation and surface radiation must be low, since emissivity is low under these surface conditions. An aluminium oxide layer covers the aluminium surface and protects aluminium from the atmosphere. Absorption will change during heating, depending on the surface layer. If absorption of solar radiation and surface radiation must be high, high emissivity is needed. Given this highly reflective surface, Kathuria (2003) reports that increase in absorption of laser radiation can be achieved by surface sample modification with emery paper or a sand-blasting technique, followed by black spray coating.

Two major phenomena resulting from solar beam–aluminium interaction can be observed during solar heating of aluminium, as is generally the case with other metal. First, energy from the solar beam heats the surface of the material, as occurs with laser (Haferkamp et al., 2004). Second, when intensity is high enough, the aluminium begins to melt. If an aluminium-specific threshold is exceeded, however, the aluminium begins to vaporize due to the presence of a protective atmosphere. Under other conditions, the aluminium is strongly oxidized.

Concentrated solar energy enables a rapid precursor heating rate (Cambronero et al., 2010), which avoids problems related to low decomposition temperature of the foaming agent (TiH_2). Once expansion of the melted precursor is achieved (Fig. 2), foam structure is completed in a few seconds. Heating must then cease immediately and rapid cooling occur to prevent precursor overfoaming. The solar furnace can be turned off quickly, and cooling through the foam plate can decrease precursor overfoaming.

Heating rate to precursor foaming can be as high as the thermal shock resistance of precursor, or metallic mould (if used). High heat transfer is thus possible in metals such as aluminium, which has a very high specific heat, and the cooling rate is faster than with conventional furnaces. More importantly, foam does not have to be