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# Evaluation of Methods of Soldering AlSi and AlSi-SiC Particle Composite Al Foams

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**The cellular structure and unique properties of aluminum foams are the reason of their numerous applications and interests in respect of their joining. The paper includes the characterization of the essence of properties and application of aluminum and aluminum composite foams, the limitations, and possibilities of their soldering. The aim of the research is the consideration of methods of soldering AlSi foams and AlSi-SiC composite foams, and the joint structure. EDS and XRD investigations of the AlSi-SiC composite foams' joints were done. The possibility of soldering AlSi9 foams and AlSi9-SiC composite foams using S-Bond 220 solder was confirmed, and higher tensile strength of the joint than the parent material was also ascertained**

**Keywords** Al foams soldering, AlSi foams, mechanical properties of soldered joint, SiC composite foams

## 1. Introduction: State of the Art

Aluminum foams, due to their high porosity, often exceeding 90%, are a group of materials, characterized by a number of unique properties, such as high stiffness, low density, acoustic wave, and mechanical energy absorption capabilities. These qualities make the foams attractive for many industries, such as shipbuilding, machine building, civil engineering, or automotive industry. The above-mentioned applications require reliable and durable methods of joining, which correspond to the type of construction. One of the possible methods of joining metallic foams is soldering. Aluminum foams volume-wise consist mostly of voids. They can be described as metal-gas composites, so that the phenomena that can be observed during soldering have two main roots. When the interface of soldering alloy and foam cell wall is considered, the metallurgical joining mechanism is basically identical to the one observed in case of soldering nonporous materials. However, global phenomena that distinguish metallic foam soldering from processing nonporous elements of the same grade alloys are difficulties of foam edge preparation, variable soldering gap, infiltration of the molten soldering alloy and flux into the foam, problems in thorough surface cleaning, excessive solder usage, and plastic deformation of foam cells during soldering.

Ashby et al. (Ref 1) claim that the best results can be achieved when aluminum foam sandwich structures—panels made of an aluminum foam and two dense face sheets, or foams with skin layers—are used as base materials. This is because the nonporous layer of metal prevents the flux from infiltrating the foam, and therefore the flux can be thoroughly removed. Those authors notice that the fluxes used for aluminum soldering are corrosive, and traces of flux left behind can lead to electrochemical corrosion. Bernard et al. (Ref 2) provide the same argument. It is only partially in agreement with authors' own research on fluxes for soldering aluminum: the literature focused on soldering states that both active-corrosive and passive-noncorrosive fluxes for soldering aluminum exist. Therefore, it must be stated that flux usage does not have to be abandoned in case of open porosity; it must be limited to passive fluxes instead.

Bernard et al. (Ref 2) also compare various methods of bonding aluminum foams to sheet metal: riveting, gluing, soldering, and welding. For soldering, S-Bond 220, SnAg4Ti4 alloy was used. Bending tests have shown that weight-related maximum load of investigated sandwich structures was not so favorable in case of soldered joint as in the case of gluing, welding, or riveting combined with gluing. During tensile shear tests under oscillating load, load, as well as stress in case of soldered sample, was lower than that in case of a glued one, which would suggest that, during soldering, the heat input influenced the foam properties.

Papers presented so far suggest that a feasible method of soldering aluminum foams, especially the ones with opened cells, is fluxless soldering. However, they estimate that the possible strength of the joint will be significantly lower than those in case of foams with surface skin layer and their soldering using flux.

Ashby et al. (Ref 1) indicate that removal of oxide layers in case of fluxless soldering aluminum foams may be problematic. They claim that soldering without the use of flux requires at least partial removal of oxide layers to allow a direct contact of a solder with a foam surface, which can be difficult due to its developed geometry. It can be performed by rubbing metal surface under molten solder with a tool of appropriate tip shape or a metal brush. As a possible solder, the use of S-Bond 220-SnAg4Ti4 alloy with micro additives improving wettability, with a melting temperature ranging between 220 and 229 °C, is suggested (in the current manufacturer's brochure, it is stated that the temperature is between 240 and 260 °C). S-Bond

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process is a fluxless soldering that is based on mechanical activation: during soldering, the layer of oxides is mechanically damaged, and then the solder propagates under the oxide layer, over the surface of a substrate.

Sendliakova et al.(Ref 3) investigated the strength of foam specimens soldered with Sn90Zn alloy. The melting point of the solder was 205 °C. Those authors claim that a possible way of removing oxide layers is either rubbing the surface with appropriate tool under the molten metal or using a flux.

The thesis, which was also specified in the previously mentioned papers, (Ref 1, 2) that the strength of a joint when foams without outer nonporous layer are soldered is expected to be considerably lower than when such a layer exists, is repeated. Results of the examinations of the strength of foams and soldered joints are presented. Maximal tension for specimens of 1 g/cm$^3$ density was 10 N/mm$^2$. Tests were carried out on Instron universal testing machine, at the speed of 0.1 m/min. 200-mm-long tubular specimens made of AlSi12 foam, and of 10-mm diameter, were used. Strength of the joints came out to be significantly lower than the foam itself. However, the destruction occurred not in the joint, but in a heat-affected zone. It suggests that the base material was weakened by the heating and cooling cycle while soldering.

All the processes that were described so far described technologies for bonding with the use of solders characterized by melting point below 450 °C, which leads to qualifying the process as soldering. In mechanical engineering, however, brazing is a much more common method. The reason is that brazing ensures higher strength and reliability of the joint, resulting primarily from the dominating diffusive character of the bond. Brazing is subject to numerous norms, considering aspects such as destructive and nondestructive testing of joints, technology commissioning, and examination of solders. The use of soldering and brazing was investigated by Nowacki, Grabian, Krajewski (Ref 4). The brazing resulted in a local melting of the foam cell walls. It was ascertained that the low strength of the foam does not justify the choice of brazing over soldering. Because of the low melting point of the aluminum itself, usually around 550 °C, significant drop of mechanical properties of the parent material can be expected when brazing is concerned. The proper direction toward aluminum foam soldering optimization seems to be to work out a process requiring low operating temperature, thereby allowing the parent material to maintain its full strength, and providing a joint the strength of which exceeds that of the parent material at the same time.

Shirzadi, Kocak, Wallach (Ref 5) investigated a process of brazing a 316 stainless steel foam to a bulk alloy of the same grade, using Cu-Ti alloy as filler metal. During tensile strength tests, the joint proved to be stronger than the stainless steel foam. No visible degradation of foam structure occurred.

Jarvis, Voice, Goodall (Ref 6) investigated methods of joining open cell nickel foams to Ti-6Al-4V plate by means of brazing, using Ti-Cu-Ni braze powder combined with various carrier polymers. The investigations showed that the mechanical properties of the joint depend on the binder system that is used during the process. The strength tests showed that, in case of shear tests, formation of boundary layer plays an important role to achieve good strength.

Longreich et al. (Ref 7) researched the possibility of joining Ni-based open porosity foams with solid Fe-and Ni-based material. Methods such as capacitor discharge welding, laser beam welding, and laser beam brazing were investigated. The methods characterized by a minimum input of energy was chosen to reduce the impact of the process on the foam structure.

## 2. Soldering Composite Foams

Soldering of Al foams reinforced with SiC particles has not been, according to authors' knowledge, the subject of any previous publications. However, trials of soldering of nonporous profiles made of this material had been conducted. These researches were carried out by Lu et al. (Ref 8). The difficulty in joining Al-SiC composite lies in the fact that direct wetting of a surface with the conventional solders does not occur, as it is stated. The current authors present an innovative method of surface preparation, which was worked out to promote wetting of the composite. The proposed method relies on plating the surface of the substrate with a layer of nickel. This allowed them to obtain a joint between a composite, containing 55% of volume SiC particles with Covar 4J29 (Fe-Ni-Co) alloy. As a solder, zinc-based multialloy was used (Zn-Cd-Ag-Cu) with a melting point of 400 °C. Macrostructural examination of metallographic specimens showed that the nickel layer reacted with the molten solder. Fractographic analysis of the specimen destructed in a static shear test showed that the failure occurs in the composite, proving good bond between the joint constituents. It was also stated that the route of achieving direct wetting of this composite is through the creation of an intermetallic layer.

Dybkov (Ref 9) describes examination of intermetallic layers, where, as parent material, pure cobalt was used, and multicomponent tin-based alloys were used as solders. The variable was soldering time, ranging from 300 to 1800 s. The experiment that was carried out led to a conclusion that the commonly assumed hyperbolic layer growth kinetic is not a good estimation of this phenomenon. It was concluded that growth of the intermetallic layers can be described with complex equations. The difference between the thicknesses of the layers, even when extreme time values are considered, was low in extent.

As previous publications indicate, aluminum foam soldering can be conducted using solders commonly used for aluminum.

**Table 1 The results of static tensile tests of the joints of AlSi9 and AlSi9-SiC composite foams as a parent material and the S-Bond 220 solder**

| Parent material | Yield strength at 0.2% offset | Static tensile strength Rm, MPa | Fracture place |
|---|---|---|---|
| AlSi9 foam, porosity 80% | 1.4 | 3.1 | AlSi foam |
| AlSi9 foam, porosity 90% | 1.3 | 2.7 | AlSi-foam |
| AlSi9-SiC composite foam, porosity 80% | 1.6 | 3.2 | AlSi-SiC foam |
| AlSi9-SiC composite foam, porosity 90% | 1.4 | 2.5 | AlSi-SiC foam |

Due to low melting point of foams and their relatively low strength, it is not advisable to use brazing. Some technological difficulties must be taken into consideration, such as infiltration of solder and flux into a foam structure, difficulty in a removal of an oxide layer due to developed surface area of a foam, or possibility of degradation in strength resulting from a heating and cooling cycle. Soldering of Al-SiC composite foams has not been the subject of any known research. However, the papers concerning soldering nonporous elements suggest that obtaining an acceptable joint may be challenging.

Publications presented so far concern properties of joints of aluminum foams with outer nonporous layer in the form of sheet metal or generally describe possibility of obtaining joints of foams with pores that are exposed on the surface. It can be remarked that there is a lack of research concerning soldering foams without surface skin or soldering composite aluminum foams reinforced with SiC particles. The aim of this paper is to fill these knowledge gaps and to provide guidelines for selection of optimal solder as well as evaluation of properties of the joints.

In most of the cases, foams need to be cut to a desired shape prior to bonding. The evaluation of surface quality, obtained by cutting using various methods, was done by Krajewski and Nowacki (Ref 10). Following methods of were investigated: band saw cutting, circular saw cutting, water jet cutting, plasma cutting, laser cutting, and electric discharge machining (EDM). Although the interpretation of the results was focused on welding-related requirements, the results are also to a large extent applicable to other joining methods. On the basis of macroscopic, visual, and electron microscope examinations of resultant structures as well as profilometer measurements, laser cutting, EDM, and water jet with abrasive were chosen do be the most favorable methods.

## 3. Experimental Part: Soldering Aluminum Foams

As a parent material, foams of 80 and 90% porosity, made of AlSi9 alloy were used. The foam production route was continuous casting with injection of gas into liquid metal. Initial trials of soldering using various solders for aluminum were made. Two of them that showed the most favorable properties, such as high melting speed and good wettability of investigated substrates, were chosen. First among the solder materials that was chosen is a commonly used InstalFit ZnAl22 alloy, with a flux in a core, supplied in Ø2, 500-mm rods, with melting temperature range of 440-470 °C. As a heat source, butane-air torch was used. The solder was applied to previously cleaned, adjoined constituents of the joint. The surfaces of the foams that were in contact were wetted by the molten solder that propagated through gravity and capillary forces.

As a comparison solder, Euromat S-Bond 220, SnAg4Ti4 alloy was used. According to the manufacturers' brochure (Ref 11), in specific conditions, this solder reacts with the substrate, even in case of materials that are considered to be difficult to solder, such as ceramics, which allows wetting to occur. It is a tin-based alloy, with an addition of nearly 4% silver and titanium and active micro additives to improve wetting (Ce, Ga). The melting range of the alloy is 240-260 °C, which allowed for the use of a 2000 W electric heating gun.

Because of weak capillary forces, relatively high viscosity of the solder in a liquid state, and a need to destruct an oxide film on the substrate, soldering with SnAg4Ti4 alloy requires conducting the process in following steps:

– Heating the elements that are joined to the melting point of the alloy.
– Covering both surfaces with a solder.
– Propagating the solder over a whole surface simultaneously destructing the oxide layer by scrubbing, oscillation, vibration, or using ultrasonic waves.
– Removing top layer of oxidized molten alloy and adding new layer of fresh alloy.
– Mechanical activation of the joint, realized through performing relative movements of the joined elements.
– Securing the joint components, applying a pressure in the normal direction to the joint surface, leaving the joint for cooling in a calm air.

Both the solders wetted the surface of the aluminum foams. However, while ZnAl22 showed lower viscosity and was spontaneously propagated over the surface, SnAg4Ti4 solder was present only in the areas, where it was introduced during soldering. The lack of solidified solder drops on the surface of substrates in both the cases is an advantageous quality.

The amount of filler in case of ZnAl22 solder was sufficient to wet the specimen's entire cross section, and the supply was cut off as soon as it stopped infiltrating into the joint. During the process when SnAg4Ti4 solder was used, the amount of filler metal was also ample-in this case, all the surface pores were filled so that when the joined elements were placed together, the excessive alloy was expelled to the edge of the joint.

In order to examine the joining mechanism of SnAg4Ti4 solder, metallographic specimens were prepared and observed under electron microscope. Image in the upper left corner of Fig. 1 presents the microstructure of the joint. In the lower part of the joint, microstructure of solder is seen—spheroidal, Ti-rich areas; and smaller, Ag-rich in a background of tin. The analysis of the distribution of elements leads to the conclusion that the main bonding mechanism of the joint results from the Ag-Al compound formation in the interfacial layer.

## 4. Al-SiC Composite Foam Soldering

Aluminum foams reinforced with silicon carbide particles, making up about 15% of their volume, were used as a parent material for the research. The composite foams were made in the same route as the aluminum ones that were formerly described. Initial trials of soldering, using zinc based solders that are commonly used for aluminum, were conducted without any success as wetting of the surfaces could not be achieved. Problem of SiC-reinforced aluminum wettability is mentioned in one of the papers described in the introduction(Ref 6). The trial of soldering with SnAg4Ti4 alloy led to achieving a joint, which can be described visually as acceptable. Wetting was possible, as the manufacturer claims, due to micro additive's content, helping the solder to propagate also in case of materials such as ceramics or oxide-reinforced metal composites.

The investigations of the solder manufacturer indicate that there are two possible mechanisms of obtaining the joint. The first one, less favorable from the point of view of mechanical properties, is an adhesive joint (Ref 10).

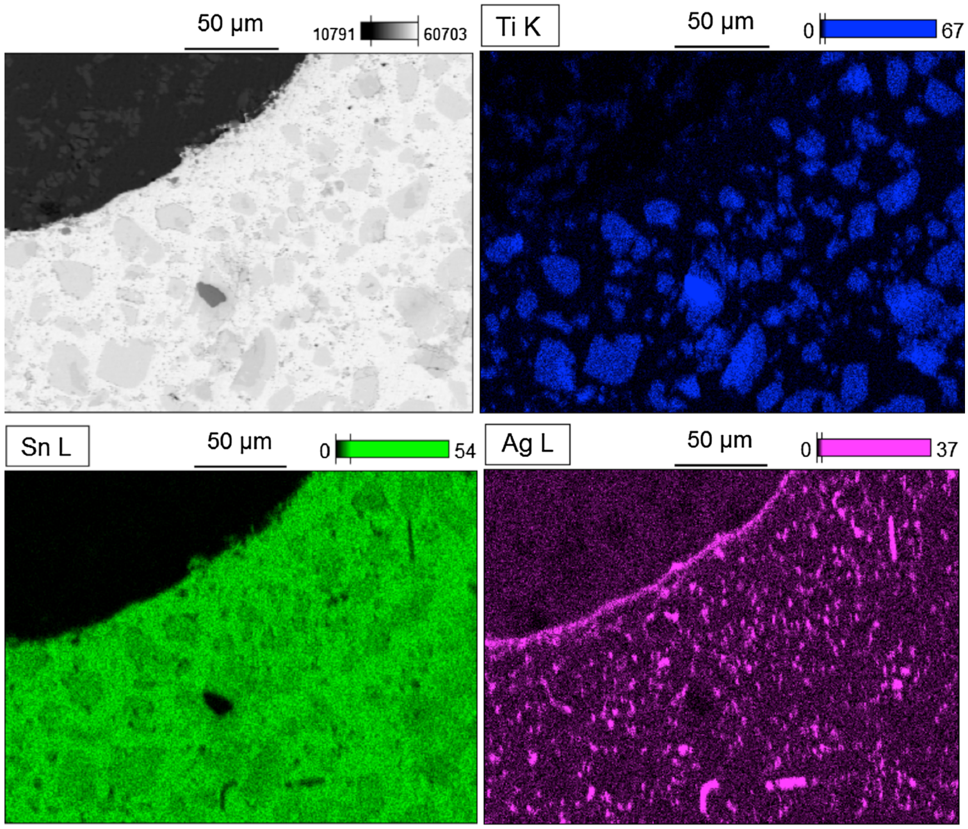


**Fig. 1** Back scattered electron image and EDS mapping of a SnAg4Ti4 soldered Al foam joint

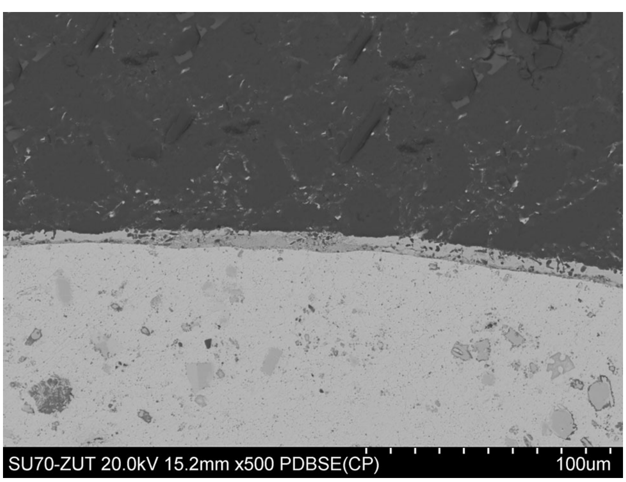


**Fig. 2** A joint with interfacial layers, bright area-SnAg4Ti4 solder, dark area-composite Al-SiC foam, secondary electron image

In this case, the bond is attained by partial destruction of the oxide layers, by rubbing, brushing the surface, or using ultrasonic under a layer of molten solder covering the substrate, to allow for a direct contact between the atoms of both phases.

The joint of the second type, as the manufacturer claims, incorporates the interfacial layers and has much greater strength. It is achieved when ceramics is joined by heating in elevated temperatures in inert atmosphere. Under these conditions, chemical reaction between the solder and ceramic surface occurs. Resultant joint has much more favorable mechanical properties that are even better than those in case of most of ceramics-metal joints, made with multilayer plating/galvanization with Mo-Mn layers (Ref 10).

The trials of manual soldering Al-SiC composite foams with SnAg4Ti4 alloy using hot air as a heat source resulted in joints that were, depending on the soldering time, weaker or stronger than the parent material. Short interaction time of the solder with the foam (30 s) and less intensive mechanical fracture of the oxide layer resulted in a joint of marginal strength, whereas longer soldering time (300 s) combined with vigorous mechanical punctuation of the oxide layers, led to a joint stronger than the joined foams. It was expected that the differences result from different joining mechanisms which were caused by varying joining conditions. Cross sections of the joints made under various conditions were prepared and investigated under electron microscope.

Less-intensive parameters led to an adhesive joint. The strength of this joint depends to a great degree on the surface development of the parent material, and it relies on the mechanical attachment of the solder in the foam surface geometry.

Longer heating times, combined with intensive mechanical propagation of the solder over the foam surface, resulted in interfacial layer formation that can be seen in Fig. 2.

For interfacial phase layer identification, x-ray diffraction examination of the specimen was made, the outcomes of which are presented in the Fig. 3. Among the easily recognizable peaks, representing the phases that are known or were expected to appear, the spectrum parts representing interfacial compounds could not be certainly identified due to insufficient contents of these compounds in the specimen. The most probable compounds, not taking oxides into consideration, were estimated to be $Ag_3Al$, $Ag_2Al$, $AlAg_3$, TiAl, $TiAl_2$ and $Al_2Ti$.

Further electron microscopy examinations were carried out. The distribution of the elements, obtained by EDS mapping is shown in Fig. 4. Only elements, concentrations of which appeared to be dependent on the interface proximity, are shown; otherwise, they were considered as not taking any part in bonding mechanism.

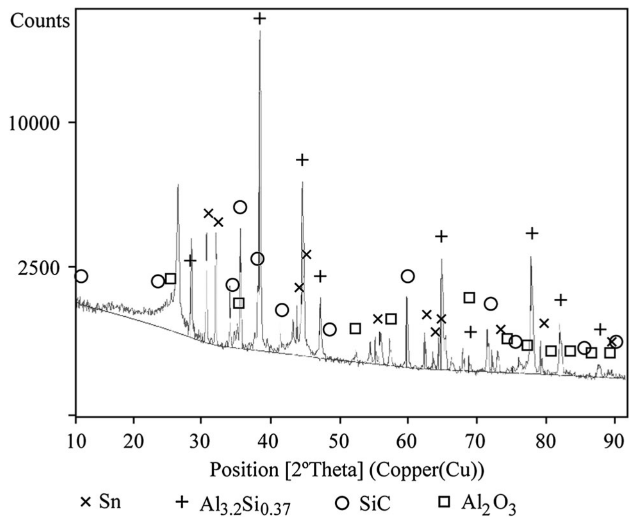


**Fig. 3** Diffractogram from an XRD analysis of a SnAg4Ti4 soldered Al-SiC composite foam joint

The lower part shows only marginal share of chemical bond, and the concentration of any of the solder elements in the joint vicinity is negligible. In contrast, in the upper part of the joint, pronounced concentration of silver, followed by some degree of titanium, is visible. From this zone, the tin was displaced. In both cases, oxidation of the interface zone can be seen. The distribution of the oxygen was not shown, as oxidation can be considered normal in case of the process that is conducted in the air.

Obtaining two mechanisms in one joint was possible due to the specification of soldering process, and both the joined foams were covered with solder separately; thus, applying different parameters was possible.

To evaluate the phase contents of the interfacial layers, spot EDS analysis was carried out. A number of points located on both layers were chosen (at least 10 points for every layer), and then the average content of the elements that were considered was calculated. The resultant elements' contents are presented in Fig. 5.

In both the layers, the atomic relation of silver to aluminum is in almost 2:1 ratio, which indicates that the soldering resulted in the creation of $Ag_2Al$ intermetallic compound. This compound was considered as one of the possible compounds from the XRD examination. A significant oxide content can be seen in both these layers; its source is long-lasting preparation process, when the air had free access to the molten solder. The oxygen concentration follows the tin and titanium concentration, which suggests that the oxygen in the interfacial layers is mostly bond with these metals, presumably in forms of $SnO_2$ and $TiO_2$ oxides Fig. 6. The proportion of the elements in the

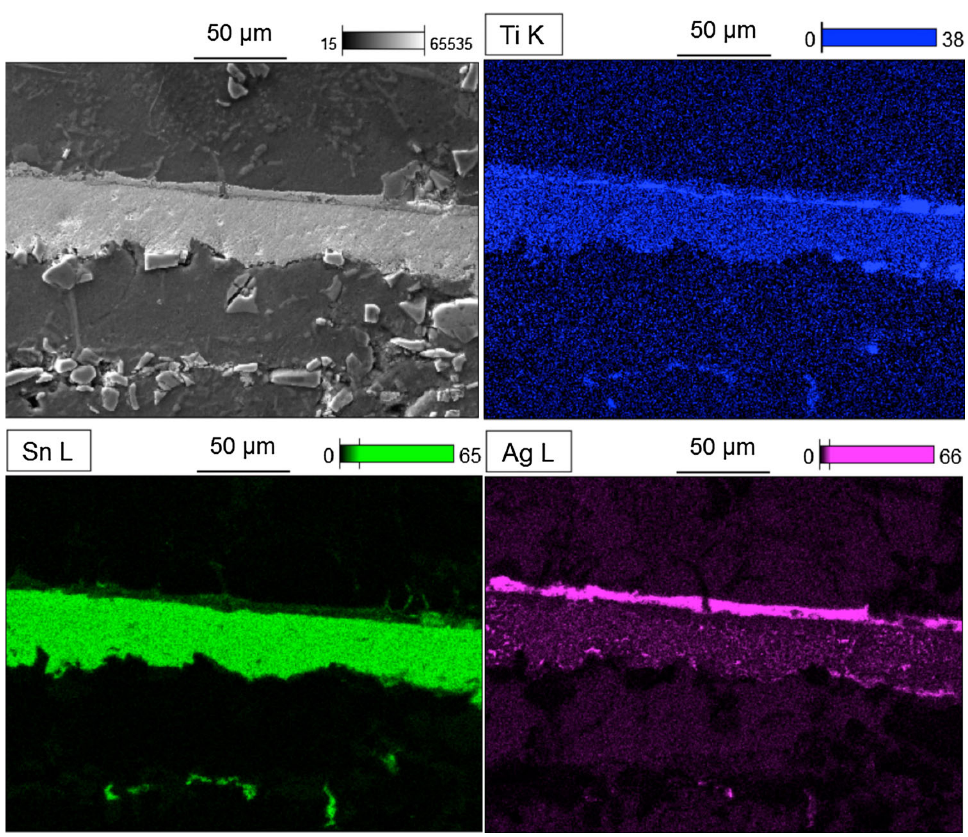


**Fig. 4** Back scattered electron photography and EDS mapping of a SnAg4Ti4 soldered Al-SiC composite foam joint. Two joining mechanisms are revealed-adhesive (lower part) and chemical (upper part)

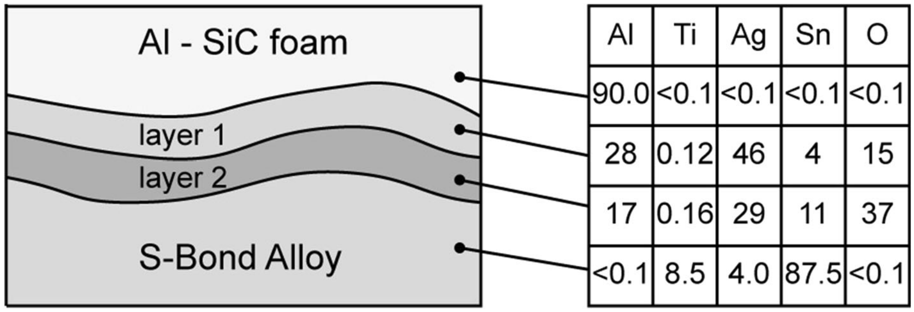


**Fig. 5** The composition of the selected elements in interfacial area, atomic percent

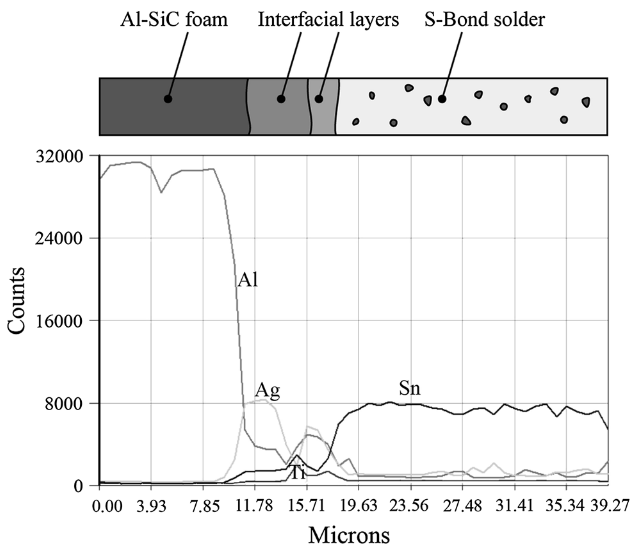


**Fig. 6** Line-scan EDS analysis of the interfacial area of Al-SiC-SnAg4Ti4 solder interface

layers suggests that the compound composition is alike, only the rates of the compounds differ. As the static tensile strength results are satisfactory, in case of materials of such a low strength as aluminum foams, introducing an inert atmosphere to prevent oxidation does not seem to be required.

It can be assumed that the dynamic of variability of individual elements concentration profile in the joint will differ depending on the nature of the interface layer phase structure. In case of solid solution, where diffusion processes take place, gradient, smooth transition of the concentration of individual elements can be expected, while in case of stoichiometric, intermetallic compounds, the transition curves are expected to be steep in the interface area.

The curves that were obtained during the tests, show that the concentration of all the elements changes basically in one point which is another confirmation of the primarily intermetallic nature of the interfacial layers.

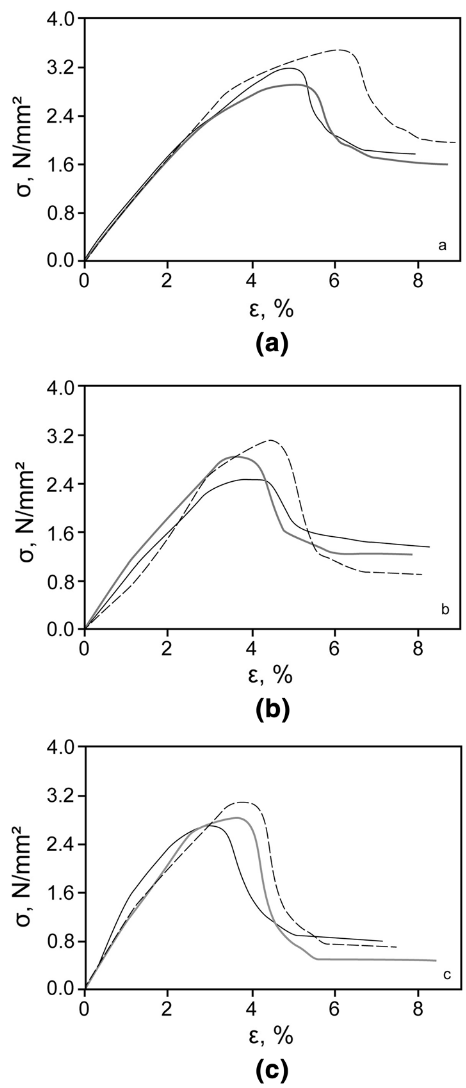


**Fig. 7** Example stress-strain curves obtained in a static tensile test for 90% porosity specimens: solid piece of foam (a), soldered with SnAg4Ti4 (b), soldered with ZnAl22 (c)

## 5. Mechanical Properties of Soldered AlSi Foam Joints

To evaluate the mechanical properties of solder joints, specimens with both the above mentioned solders were prepared and a static tensile test was conducted. The tensile strength tests were carried out on Instron 5585H universal testing machine, at the speed of 1 mm/min. The gauge length of the specimens was 80 mm, the cross section of $25 \times 25$ mm$^2$. The specimens consisted of two pieces of foam, butt-joined according to the respective directions, described in the introduction. As a reference, the strength of parent material was also measured. The destruction occurred in the foam zone in all cases of the test.

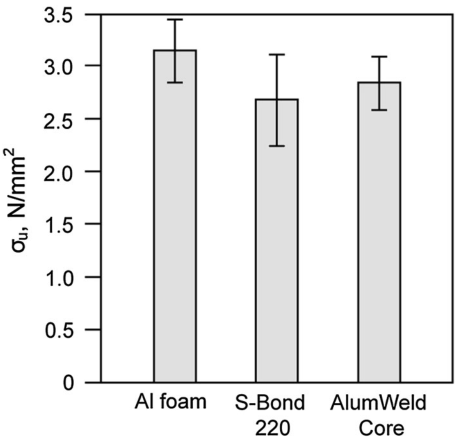


**Fig. 8** Average ultimate tensile strength for 90% porosity specimens, the error bars represent standard deviation

Exemplary stress-strain curves for investigated specimen types are shown in Fig. 7. Due to significant variation of the test values, conclusions should not be based solely on presented data. The curves are typical for brittle materials. Yield strength at 0.2% offset was 1.4, 1.3, 1.5 $N/mm^2$ for parent material, SnAg4Ti4 and ZnAl22 soldered samples, respectively. The average static tensile strength for both the specimen types as well as for the parent material, including standard deviation, is presented in Fig. 8. Taking the calculated measurement uncertainty into account, the strengths can be considered equal. Results that were achieved are presented in Table 1. They are comparable with the ones obtained by Sendliakova et al. (Ref 3) for considered porosity. However, in the mentioned studies, a significant drop of strength was noticed in case of soldered specimens compared to parent material, which does not tally with the results of this study.

Strength values that were measured are an evidence that the mechanical parameters of joints obtained when the process is carried out properly allow to maintain toughness equaling parameters of parent material. It is worth noticing that despite relatively high melting point of the ZnAl22 solder, above 440 °C, the process did not weaken the parent material significantly (Table 1).

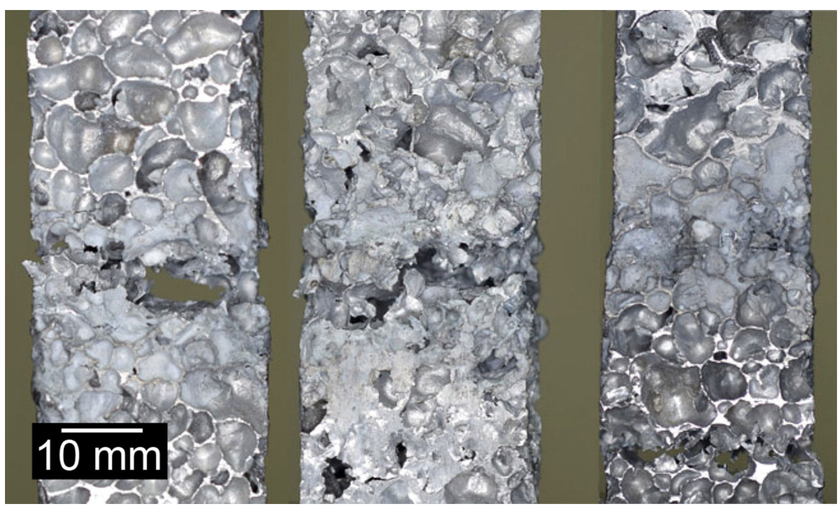


**Fig. 9** ZnAl22 soldered Al foam-Al foam specimens after static tensile test

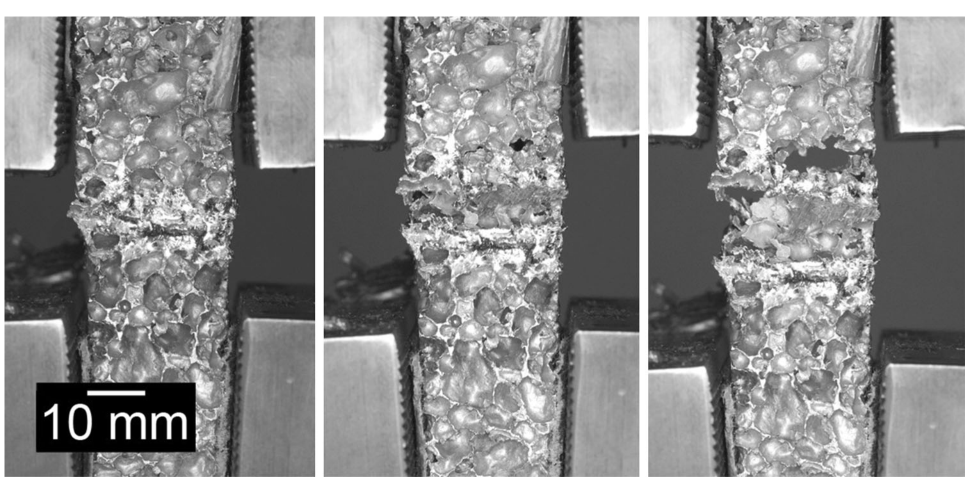


**Fig. 10** A specimen before the test (left), in a stage when most of the cross section is destructed (middle), at displacement of ~30 mm-a minimal connection is still between the parts is noticeable (right)

Figure 9 shows the specimens soldered with ZnAl22 alloy after static tensile test. The failure occurred in random areas-in proximity to the joint as well as in a distance. Because of the fact that the surfaces that were joined were initially flat, the developed surface of the fracture proves that the mechanism of destruction did not involve decohesion.

Figure 10 presents SnAg4Ti4 soldered specimen destruction. Presumably, the solder that is seen on the surface may have actually locally reinforced the foam which caused the failure to shift to a further part of the material.

## 6. Conclusions

The conclusions that can be drawn from the above study are summarized as follows:

- When proper additional materials and process parameters are chosen, soldering is a process allowing to preserve the full strength of the metallic foams.
- The joint provides sufficient parameters between composite Al-SiC foams incorporates interfacial layers, which evidences that chemical reaction between the joint constituents occurred. One or two layers were observed, the number presumably depending on the oxidation level and therefore a possibility to create certain compounds. The main joining mechanism seems to be a creation of $Ag_2$-Al compound.
- Soldering aluminum foams is a less demanding process than soldering Al-SiC foams as the base material is more easily wettable by conventional solders. The interfacial layers are less pronounced: they are not visible in SEM image; however, they can be detected in EDS examination.
- In future research, experiments that would show to what extent the filler supply can be limited while preserving the strength of parent material seem to be valuable. The amount of filler metal will definitely be more easily controllable in case of SnAg4Ti4 alloy than in cases when ZnAl22 or other similar alloy is used, because of much higher viscosity in the molten state of the first one.


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