3 Working, Joining, Material combinations

3.1 Forming, machining, coating

3.2 Joining

3.3 Sandwich panels

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3.3.1 General considerations

For structural applications metal foams are often used in combination with conventional dense metal structures such as sheets, columns or more complex shaped hollow metal structures. This allows for optimised mechanical properties in a given loading situation [1]. It also facilitates „hiding“ the metal foam inside a closed and dense structure, which again is advantageous under the aspect of, e.g., corrosion protection. Such composites containing aluminium foam may be manufactured in various ways. The most obvious and straightforward one is achieved by adhesive bonding of pre-fabricated aluminium foams and, e.g., flat face sheets. However, this approach has certain disadvantages and is not feasible in all cases. An alternative and preferable method consists in establishing composites during the foaming process. Foam-filled columns can be produced by inserting foamable precursor material into a column and then heating up column and foam simultaneously. The foam will eventually rise and fill the column. Another possibility is to start with a foamed part and to coat it with aluminium by thermal spraying [2] thus establishing a dense outer skin. Yet another way is to use the foam as a core for die-casting [3][4]. **A**luminum **F**oam **S**andwich (**AFS**) panels may be manufactured very elegantly by roll-cladding face sheets to a sheet of foamable precursor material, by then creating the desired shape in an optional working step and by finally foaming the entire composite [5][6] (see **Figure 1**). Foaming will create a highly porous core structure without melting the face sheets if the melting points of the foam and the face sheets are different and process parameters are chosen appropriately.

3.3.2 Sandwich foaming process

The formation of a metal foam sandwich may be visualised by making use of an X-ray radioscopic technique which has been developed recently [7] and allows for the monitoring of the internal structure of expanding metal foams. Since the technological implementation of the production process for aluminium foam sandwiches still suffers from occasional flaws which can be traced back to inadequate process parameters and defects in the foamable material, the x-ray radioscopic investigations may also help to identify such problems. One nice example of this is shown in **Figure 2**. The foaming of this particular sandwich panel was carried out at a furnace temperature of 750°. The first frame corresponds to an early stage of foaming. The foamable core layer already shows a slight absorption contrast to the face sheets, indicating that some porosity has already formed at this stage. Moreover, a crack may be seen on the right upper side running right through the foamable layer. The second frame, showing the situation just 5 seconds later, reveals that the foaming of the core layer takes place in a highly non-uniform way. The restricted heat flux through the face sheets leads to a temperature gradient and triggers the foaming process near the interface of face sheet and core layer. As can be seen from **Figure 2**, the crack in the precursor material has deepened after the initiation of the foaming process and still extends over the entire foam layer. After 22 seconds of ongoing foaming, however, the core layer is fully expanded and the crack has disappeared. Therefore, this type of defect does not lead to an obvious defect in the foam sandwich.

In order to obtain a complementary view of expanding metal sandwich structures, metallographic images have been made of samples which were foamed to a given expansion stage and were then quenched. Three of these images are shown in **Figure 3.** The unfoamed sample shows a sharp boundary between the foamable core – characterised by the angular-shaped grey silicon particles embedded in the light aluminium matrix - and the dense face sheets to the right. The foamed sample in the middle, which is at a stage corresponding approximately to that of full expansion, shows the typical microstructure of an undereutectic aluminium-silicon alloy. The light aluminium-rich grains surrounded by the eutectic phase can be easily identified. The dense face sheet is virtually pore-free and shows no structure in the low magnification chosen. The interface of foam and face sheet lies on a straight line and is well defined.

Finally, the foamed sample on the r.h.s. of **Figure 3** represents an even later stage of expansion. It exhibits a notably coarser grain size distribution in the foam and a slightly diffuse boundary between foam and face sheet. The eutectic phase has grown into the former face sheet material by diffusion processes and has locally amalgamated with the face sheet alloy - one reason for the excellent bonding between foam cores and face sheets in properly manufactured aluminium foam sandwich parts and the explanation of the absence of face sheet delaminations in tests of the tensile strength of sandwich structures.

3.3.3 Industrial application

On the basis of technological advantages and limitations, application strategies have to be developed in order to simplify the decision whether or not AFS (Aluminium Foam Sandwich) components should be applied in a certain production process and to avoid unrealistic decisions. The application of light weight materials often implies higher costs and, compared to steel, eventually a loss of stiffness and an increase of manufacturing problems. For a technically and economically successful application of AFS components, a new approach to vehicle body architecture is required [9].

For an application in the “Body in White” (BIW) about 90% of the current design concept requires a complete change. The space frame, for instance, should be designed considering the stiff AFS components in a way that the special properties of AFS may be optimally exploited. A simple replacement of steel parts by AFS parts will not suffice since the benefit of the stiffened planar surfaces are not employed efficiently. Therefore, a new BIW architecture must be developed. Examples for such new concepts are shown in **Figure 4** and **Figure 5.**

Whenever replacing conventional materials by AFS, it must be taken into consideration that the range of AFS properties includes some characteristics that have previously been achieved by additional parts. For example, the use of AFS for the fire wall could imply the elimination of heat shields and the associated connecting parts. The application of AFS parts may also lead to an elimination of noise attenuation materials because of the low structure-borne sound characteristics of AFS.

Another area of interest to be investigated in the future is that of exterior panel closures, e.g. doors, hoods and decklids. This application depends on the achievement of a Class-A surface with stamped AFS panels. Taking a hood stamped out of AFS as an example, there is no longer any need for an inner panel due to the inherent stiffness of the AFS outer layers, thus reducing expenses for material, tools and the complete assembly. In spite of higher material expenses, an AFS bonnet may – depending on the shape – be more cost-effective than a steel hood up to a production volume of 100,000 units. This is attributed to the reduction of manufacturing and tooling expenses. This means that light weight AFS constructions may be applied economically in low and middle production volumes due to the reduced investment costs compared to conventional steel components.

In general applications, possible additional costs of AFS panels should be compared to the advantages which can be expected. Even if only one of the improved characteristics of AFS is required for a particular application, the associated increase of expenditure may be of secondary interest. In general, the application of AFS components will increase overall material costs, so that an enhanced performance must be achieved as justification. In the future, this situation may change as vehicle operating costs gain more significance due to the higher energy costs. As a consequence, this implies that the amount of money available for the use of light materials, which is right now about 5-10 DM (2.5 to 5 Euro) per kg weight reduction, will increase.

3.3.3.1 Technological Benefits

Besides the advantages already known – the combination of high torsional stiffness with low weight – further properties of AFS must be taken into account as they also may have a major impact on the implementation strategy.

Acoustic Properties

Considering the customers comfort requirements, a new lightweight body material is not allowed to show inferior acoustic properties than steel. Therefore, the good acoustic properties of AFS should be emphasised. Especially cars with aluminium bodies show poor damping properties. To improve this situation, a large amount of damping material must be added, thus sacrificing the mass saving potential.

A joint research by the TU Dresden and Karmann has revealed that AFS offers a significantly better acoustic behaviour especially in the range of 50-400 Hz. Additional insulation measures may be reduced - weight is saved. The acoustic performance of special insulation materials will of course not be attained, so that AFS cannot exclusively serve as a sound damping material.

Thermal Properties

Thermal conductivity is another important aspect when selecting body materials. Due to the entrained air bubbles, the heat transport capabilities of foams are low. Depending on the density, the thermal conductivity of AFS is reduced to 1/12 – 1/20 of the conductivity of bulk aluminium. Furthermore, AFS satisfies most of the fire protection regulations. No adhesives are contained and the AFS components maintain their shape up to the melting point of 600°C and in some cases even above. The exceptional welding characteristics together with minimal distortion justify to characterise AFS as “thermally very stable”.

Robustness

Sandwich components, as known from aero-space technology, are relatively vulnerable in impact situations. Even small damages of honeycomb panels may lead to a complete breakdown of the core-panel structure. As a result of the metal link between core and panels, this does not occur in an AFS panel. Cracks may only occur in the core and their expansion is limited. A delamination of core and panels has not been detected with parts manufactured and tested to date. This is very important since structural body components are not subject to special checks during the product life cycle

Other Properties

Additional properties of AFS which enhance product performance are: *good energy absorption, recyclability* and *low manufacturing time periods* for the sandwich components. The foaming process, e.g., takes only 30 to 45 seconds even for large parts. Therefore, mass production with a comparably low number of parallel production lines is possible.

3.3.3.2 Technical Limitations

When selecting applications for AFS components, their formability and geometry after the foaming process must be taken into consideration. A constant component thickness may only be achieved with plane sheets. Complex formed structures will have a variable thickness in different areas of the component. However, these thickness variations are predictable and may be adjusted to component loads by simulations, since the upper layers maintain their original geometry during the foaming process. The form tolerance after foaming is ±1 mm. Drills and trim cuts will be performed with the help of a trimming/calibration tool, so that additional reference surfaces and flanges may be established. U-form shapes should generally be avoided, as they show an adverse relation between the side and base surfaces which leads to differences in the thickness of the foam (**Figure 6**). This effect is primarily due to the stiff inner layer which should shorten up when the thickness is constant.

There are limitations to the determination of the gage relation between outer layers and core due to current processing techniques. The minimum thickness of the outer layer is limited to 0.6 mm. A skin thickness less than this may cause a degradation of the alloy during foaming and is undesirable. Under optimum process conditions, the foam layer may expand up to the extent of 7 times of its original thickness. The maximum achievable height ranges from 25 to 30 mm. Thicker foam cores should be avoided because of the different cooling rates within the foam which may result in a non-uniform core porosity.

3.3.4 Joining Technology of AFS

In order to be able to efficiently exploit the advantages of AFS technology, it does not suffice to exchange highly stressed parts with AFS parts. AFS technology requires special construction as well as joining techniques, adjusted to the characteristics of sandwich parts. The joining of AFS parts may be attained by a variety of possible processes. The most important ones are given in **Table I**.

Laser welding

The process of laser welding is suitable for series production. In order to weld face sheets of 1.2 millimetres 3 kW power are required. By bluntly welding sandwiches, only the face sheets are bonded, while the core layers remain unaffected. As shown in **Figure 7**a the filigree cell structure is not damaged by the local thermal impact. In welding flat AFS sheets with linear joints, a maximum speed of 10 m/min has been achieved. If both face sheets have to be bonded, usually the part has to be turned thus decreasing the welding speed to a rate less than 5m/min.

TIG/MIG welding

Welding of AFS parts by common welding techniques is also possible. The principle techniques worth mentioning are TIG- and MIG-welding (**Figure 7b**). Both techniques are exceptionally well suitable both for joining two AFS parts and also AFS parts with aluminium parts. The advantages of these techniques include flexible application possibilities, the amount of experience in this field and the low investment costs. The high degree of stiffness of AFS sandwich parts, their low thermal conductivity and the resulting low thermal distortion rate minimise the necessary efforts for clamping and fixing the parts. As in laser welding, only the face sheets have to be welded. Welding rates for manual TIG welding reach 0.3 m/min, those for MIG welding reach 0,8 m/min. Partly mechanised welding with a linear carriage may achieve a rate up to 1,3 m/min.

Bolt/Pin welding

Another joining technology of considerable interest for AFS sandwiches is that of welding bolts (**Figure 7**c). These bolts do not transfer high forces but are employed for fixing cable bundles and wires or as mass contacts. The welding process is completely controlled and monitored with the help of a welding head with a linear motor. This technology allows for the regulation of variations of the thickness of the sandwich. As with the other techniques, the core layer remains intact in the welding area. Even welding a bolt directly onto a flaw, e.g. a void or a large pore has no impact on the quality of the bonding as the joining zone is obviously limited to the face sheet.

Punch Reveting

Due to the increase of mixed constructions and the problem of thermal impact on the structure by assembling parts by welding, this joining technology has been strongly forced in the recent years. Since 1994, Punch Reveting is applied in construction of the AUDI A8 and has reached its momentary peak in the construction of the A2 with 1800 die casts per car. **Figure 8**a shows the joining area as well as a cut of the fusion. Studies of the settling properties of the core layer have shown another positive characteristic of AFS sandwiches. If AFS is highly compressed, its tensile strength drops to a value of 50% plastical deformation, but regains the original mechanical values of the non distorted sandwich at maximum compression. This property is a result of the increasing mechanical clutching of the collapsed cell structures and the likewise increasing friction. The mechanical values of compression strength and shear stress do decrease in this range but they stabilise again at a low level under static as well as under dynamic load.

Riveting nuts and screws

Another possible joining technique consists in the placing of riveting nuts and screws (**Figure 8b**). The joint cannot transfer high forces. It is rather employed to fix holders and devices. The size of the nuts and screws may range from M4 to M10, depending on the thickness of the AFS parts and the face sheet.

Flow Drilling

Flow Drilling (**Figure 8c**) is an alternative to riveting nuts. Frictional heat is generated by a multi-polygon which is pressed onto the face sheet in axial direction at a high revolution rate/speed. The material plastifies and becomes easily formable. You will get a defined drill-hole and the material of the face sheets will flow into the core. The length of the formed hole wall will be three to five times the thickness of the face material. The minimum revolution rate for flow drilling lies at about 2400 rpm at a spindle moment of 1.5 kW. A coated thread cutter is used at a revolution rate of 500 rpm. The lifetime of the flow former and the thread cutter amounts to 10.000 drills and threads. But so far only feasibility studies have been carried out.

Riveting

AFS parts may also be riveted. Especially in mixed constructions, riveting is very well suitable. It is important to choose a relatively large diameter of the rivet head since too small a diameter leads to a fastening pressure of the rivet which compressed the core. Due to the high surface pressure you will find plastical deformations on the face sheets.

Bonding

AFS with face sheets of aluminium may be bonded with the same technology as conventional aluminium sheets (**Figure 9**). The same parameters have to be respected as there are the creation of a defined surface, a construction adapt for bonding and especially the choice of an adequate bonding system. The strength of today’s bonding systems partly exceeds the physical values of the aluminium foam cores. One of the main advantages of bonding consists in the optimal transmission of the applied forces. This technology allows the AFS parts to be excellently integrated into the surrounding structure.

3.3.5 Cutting of AFS

Cutting of AFS structures, the unfoamed precursor material as well as the foamed sandwich panels, can be quite a challenge, especially in the latter case. Here, conventional mechanical cutting techniques cannot be applied in a straight-forward way because of the danger of uncontrollable deformation of the material. Therefore, two alternative methods have been evaluated.

Laser beam cutting

Laser beam cutting of the unfoamed material has been successfully evaluated [11][12]. A high precision of cutting into the desired net-shape without the need for further processing was achieved (see Sec. 3.1).

Cutting of the foamed materials required a special adaption of process parameters to take account of the specific nature of AFS. Both face sheets have to be cut simultaneously. Moreover, the low-density foam tends to melt more than the face sheets leading to the deposition of metal and dross at the opposite side of the sandwich panel which lower the quality of the lower cutting edge [13]. Good results with cutting a 12 mm AFS could be obtained by adjusting the laser power to 5 kW and the cutting speed to 0.8 m/min.

Water jet cutting

Water-jet cutting of unfoamed AFS precursor is possible without any problems. Cutting of AFS sandwiches, however, imposes the problem, that abrasive particles remain in the pores after cutting and cannot be entirely removed even by repeated swilling with water or solvents. Such contaminations are not acceptable in cases in which the sandwich panels have to be varnished as they would lead to inferior surface qualities [14].

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Figures

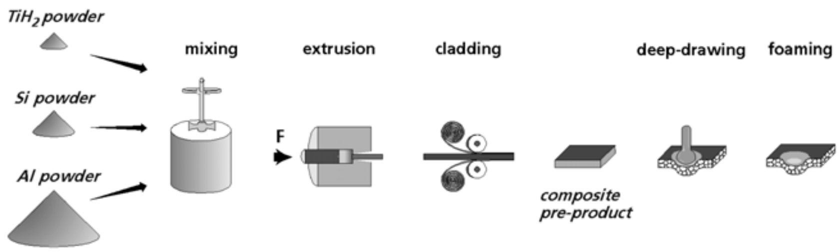


Figure 1. Process steps for making sandwich panels with aluminium foam cores.

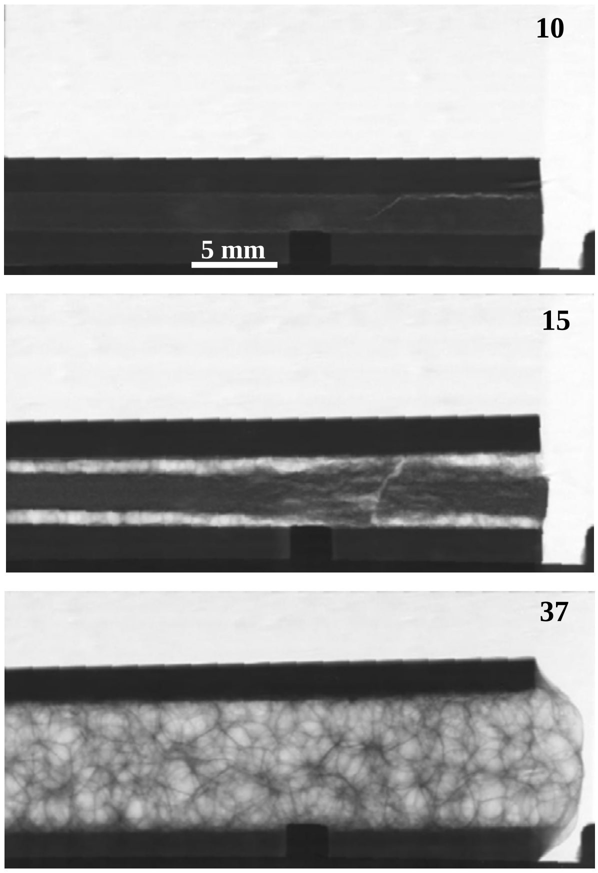


Figure 2. Series of radioscopic images of an expanding AlMn1/AlSi7-foam /AlMn1 – sandwich [8]. Foamed at a furnace temperature of 750°C.

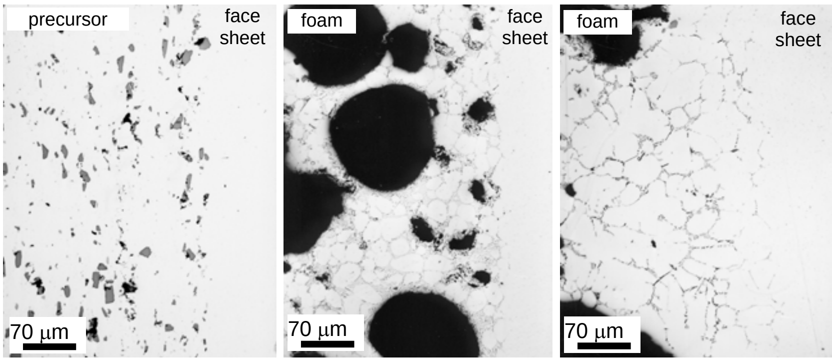


Figure 3. Metallographic images of sandwich structures with an AlSi7 core. Three different expansion stages are shown: left: unfoamed precursor material, middle: sandwich shortly before maximum expansion, right: sandwich at the onset of face sheet melting. The width of each image is 0.75 mm.

Figure 4: „Detroit Show Car 1998“ developed by Karmann (Osnabrück) for demonstrating potential uses of aluminium foam sandwich panels. The rear bulkhead and the front firewall (not directly visible) are made of AFS.

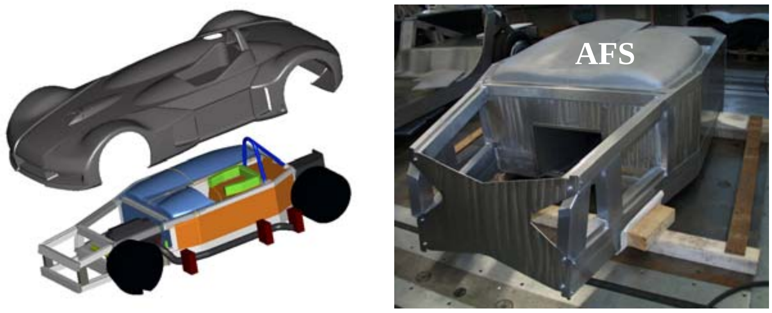


Figure 5: „EUROC 99“ concept racing car, left: CAD- Model of entire car, right: space-frame structure with AFS-parts.

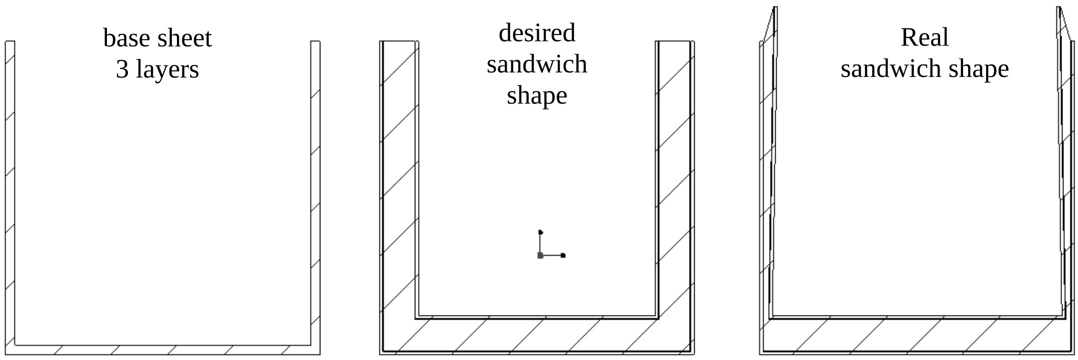
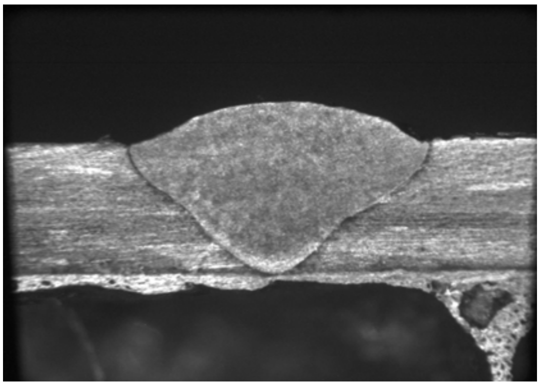
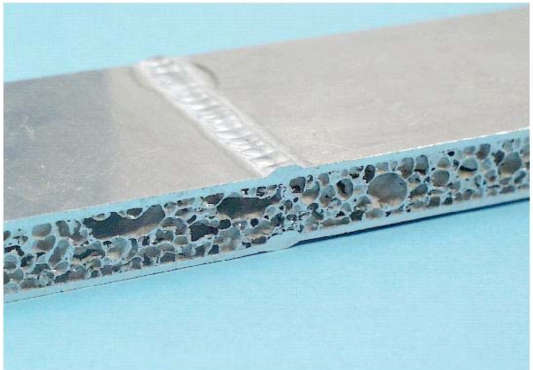


Figure 6: limitations of manufacturability of AFS



a)



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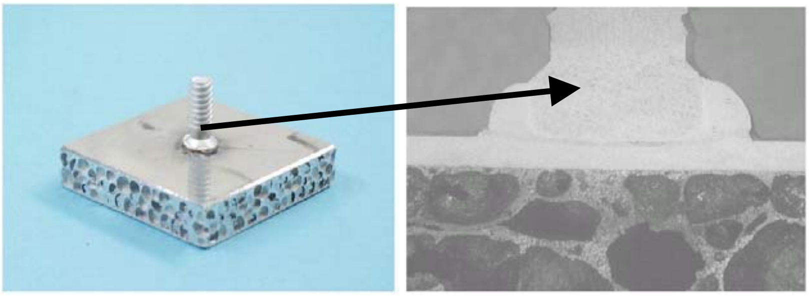

c)

Figure 7: Different welding techniques for AFS. a) Laser welding, b) TIG welding, c) Bolt/Pin Welding

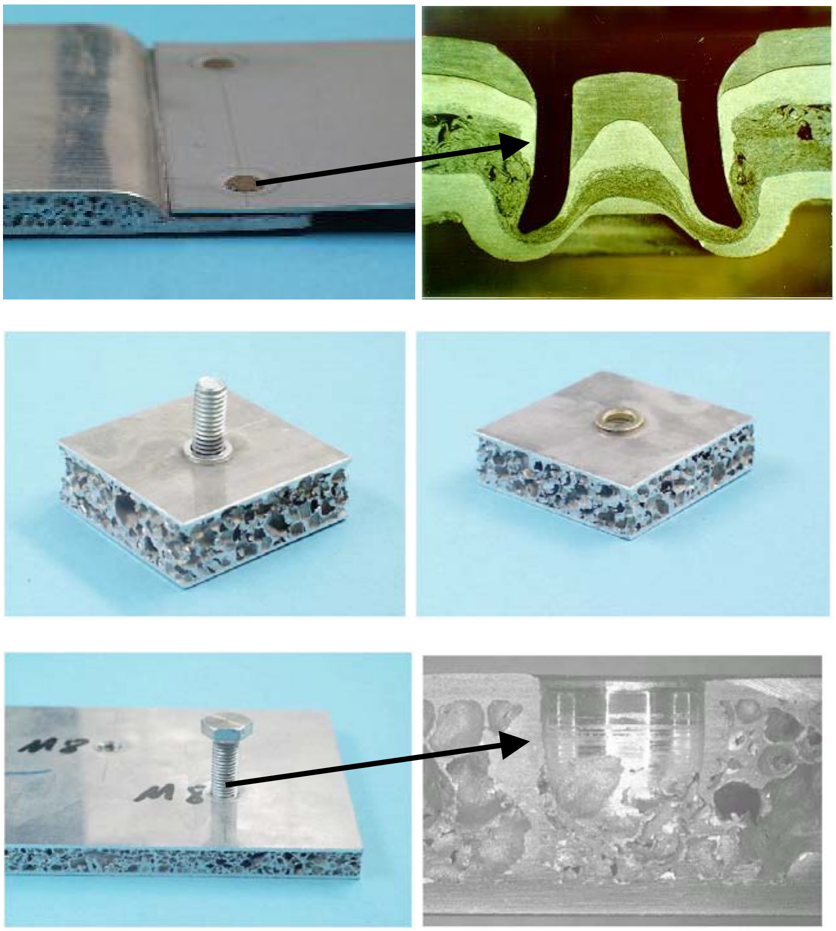

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Figure 8: Different joining techniques for AFS. a) Punch riveting, b) Riveting nuts and screws, c) Flow drilling

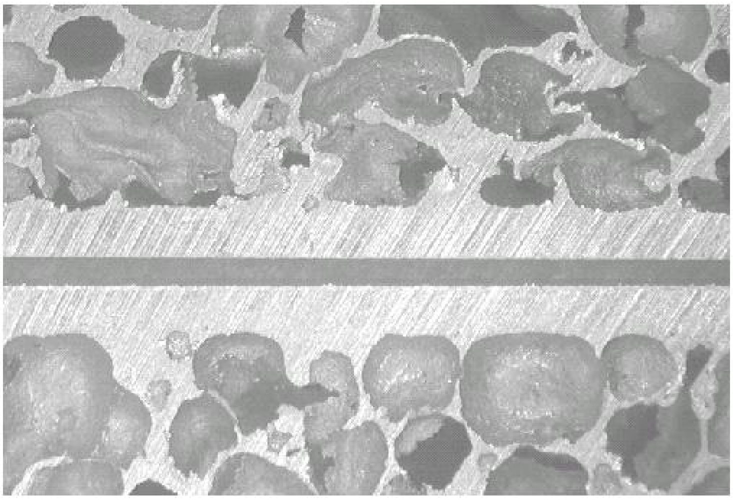

Figure 9: Bonding of AFS

Process	Details:
Laser welding	CO_2-Laser, Nd:YAG
TIG welding MIG welding	by hand, partly mechanized, by robot
Pin/bolt welding	by hand, mechanized
Punch riveting	AFS/aluminum; AFS/steel
Riveting nuts/screws	M4 - M8
Flow drilling	M4 - M8
Riveting	Blind riveting, Splay riveting
Bonding	1-K and 2-K systems

Table I: Overview: joining techniques for AFS