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Aluminium foam sandwich structures for space applications

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Abstract

Within a French/German research project the suitability of a new class of materials, so-called aluminium foam sandwiches (AFS), was tested for space applications. While classical sandwich materials require particular, cost and time intensive processing techniques, AFS are suitable for mass production technologies as they are known from car industry and the like. Thus, it is expected that such materials could essentially contribute to cost reduction in space.

In order to test the principal applicability and to gain some first experience in how the manufacture of AFS space components could work, a cone 3936 as used in Ariane 5 was chosen as demonstrator.

In the forefront, the material had been intensively tested considering mechanical and thermal properties. By means of FEM the results of these experiments were used to simulate the behaviour under load and to optimise the design accordingly.

Using AFS suitable production methods, the cone was built and tested simulating the loads during launch. The test results were compared to the predictions made by FEM and showed good agreement.

1. The project

Goal of a French–German research project has been to explore the application potential of aluminium foam sandwiches (AFS) in space components. Currently, these lightweight materials find some first applications in particular fields of mechanical engineering such as race cars, and small series of other land-based vehicles.

Despite the fact that for big mass production the material is still in state of testing and evaluation, more and more interest has been shown in it [1].

Additionally to its high potential as lightweight material, AFS offers a number of advantages compared to state of the art sandwiches. Among these advantages their flexible processability and potential of cost reduction has to be pointed out in particular.

Since so far AFS have hardly been considered for space applications, goal of the research project was to examine whether the advantages of AFS could also be used beneficially in this sector.

For this purpose, an Ariane 5 cone 3936 has been designed, produced, and mechanically tested at "prototype step" (around half of limit loads).

During this process solutions of problems resulting from the application specific requirements and in the manufacture process were focused on.

While the German activities at alm GmbH were mainly concentrated on design, calculation and

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manufacture of the individual cone segments, the French side funded and lead by the French Space Agency CNES dealt with an intense characterisation of the material, assembling, and testing of the cone.

On the German side, the project was co-funded by the German Space Agency DLR.

2. AFS—comparison to classical sandwich materials

Sandwich materials in general are typical lightweight materials and thus frequently used in various space applications.

State of the art sandwich structures are composed of a number of individual layers bonded to each other by means of adhesives. This fact yields an incompatibility to processes or applications involving heat. Consequently, they are unsuitable for joining techniques such as welding or soldering—components made of these materials have to be integrated into structures by means of screwing, riveting, and adhesives or similar.

Due to their particular structure the final shape of components made of classical sandwich materials has to be given during the manufacture of the sandwich material itself. Reshaping of the material or of components made thereof is usually not possible. Thus, structures made of classical sandwich materials are either flat or have to be individually manufactured while accepting high production costs.

In contrast, AFS do not have the above disadvantages.

As shown in Fig. 1, AFS consist of two external aluminium sheets and an internal layer of aluminium foam. Since the layers are bound to each other metallically, the sandwich is free of any adhesive and suitable for welding.

While AFS have the advantages of classical sandwiches such as high stiffness and low weight, they can be reshaped by technologies well known from metal sheet materials. As this will be evident from the production process shown below, processes well known from mass production such as deep drawing or pressing may be applied.

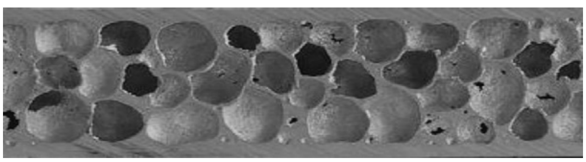

Fig. 1. Cross-section through AFS showing two external aluminium sheet layers and an aluminium foam core in between.

3. AFS—production process

During the last two decades several processes [2,3] for the manufacture have been developed being more or less suitable for a repetitive mass production. Common to all these processes is that they start off with sheets of cover layer material and a powder mixture for the core. Besides aluminium powder as main component, the mixture contains alloy elements and a gas propellant in powder form. Typically this gas propellant is TiH_2, releasing hydrogen if exposed to high temperatures.

In the production process developed at alm and used for the current project, a container is built from the cover layer material, filled with the powder and sealed.

As shown in Fig. 2 the container is subsequently compacted, whereas the powder mixture in the inner reaches a density just a few percent below the theoretical density of 100%.

Simultaneously the now solidified core is metallically bound to the cover layer material.

By rolling of the compacted container in a conventional rolling mill for aluminium, sheets are produced comprising three layers:

- Two cover layers at the outside resulting from the walls of the container.
- A core layer in between resulting from the original powder filling.

As already mentioned above, the precursor sheets obtained from milling can be processed like conventional aluminium sheets. Thus, reshaping technologies known from mass production such as deep drawing or pressing can be applied.

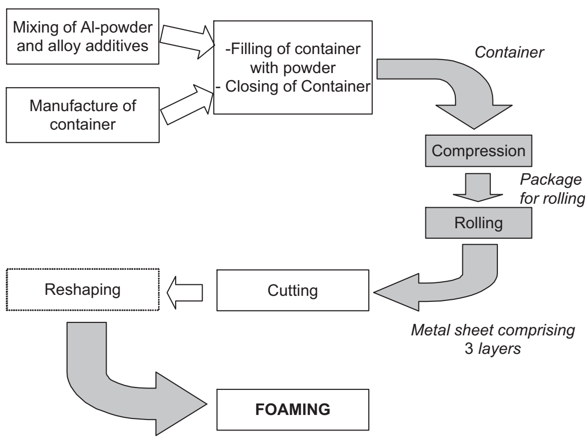

Fig. 2. alm—production process of AFS.

In a subsequent foaming process the metal sheet is heated up to a temperature range where the core layer turns liquid but the cover layers still stay solid. It is evident that this restriction has to be taken into account by adequate material selection.

However, the gas propellant mentioned above is adjusted that way that it starts to release gas (hydrogen in the case of TiH_2) while the core material is in its liquid phase. Thus the core starts to foam and to develop the porous structure shown in Fig. 1. On subsequent cooling, this structure is frozen.

Since the cover layers stay solid during the foaming process the original shape of the sheet material after reshaping has been fairly preserved but the thickness has increased.

Nevertheless, depending on the geometry a recalibration of the sandwich may be applied in order to compensate for smaller deformations that occur during the foaming.

It is evident that the ratio of thickness of cover layer and core material of the precursor is already adjusted by the dimensioning and filling of the container before rolling.

The rolling as such only permits the reduction of the overall thickness of the precursor but hardly influences the thickness ratio of the individual layers.

The expansion rate of the core material during foaming; however, is controlled by the amount of foaming agent in the mixture and duration of the foaming process.

Taking these aspects into account, a sandwich can be tailored according to application specific requirements.

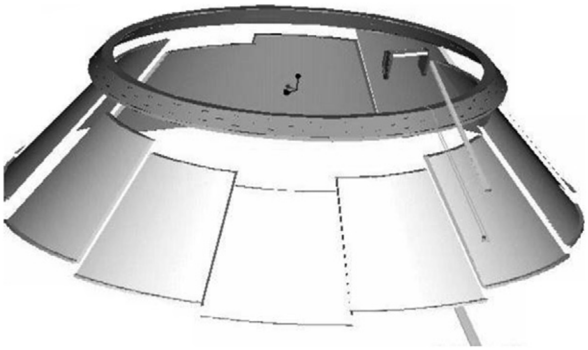

Fig. 3. AFS-design of the cone comprising an upper ring and 12 AFS segments with integrated flange at the bottom.

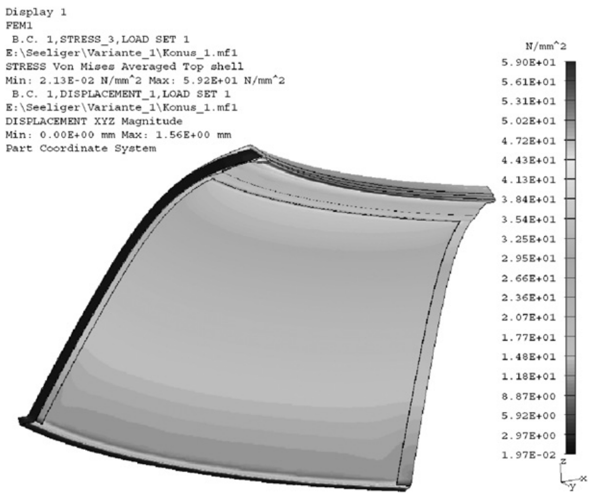

Fig. 4. von Mises stresses for the cover layers and upper ring.

4. Cone design and calculation

During the design phase, several technical solutions for realising the AFS cone were taken into consideration. The individual designs varied mainly in shape of the cone segments and the number of individual segments the cone was to be composed of.

As shown in Fig. 3, the design finally chosen consisted of 12 individual AFS cone segments comprising an integral flange at the bottom for the attachment of the cone. The upper part of the cone was finalised by a ring unifying the individual segments and also transferring the loads into the cone structure.

The AFS-configuration chosen consisted of ENAW 6060 as cover layer material and AlSi6Cu10 for the foam. The sandwich had an overall thickness of 25 mm with cover layers of 1.5 mm thickness.

This configuration had been extensively examined and characterised by various French institutes under the guidance of CNES. The material data thus obtained were used as base for FEM.

Based on the loads given in specification DLA-NT-0-528-SDT–19/04/2001 the design was examined: stresses and deformations were calculated for forces perpendicular and parallel to the plane of the upper ring and a momentum around its centre.

As there can be seen from the FEM calculations (Fig. 4), the cover layers of the upper part of the AFS-segments and the upper ring were loaded most. However, already from a pure geometric point of view this result is plausible.

By increasing the thickness of the ring profile, this effect was compensated for in the final design.

In contrast, the stresses inside the core were rather small and clearly below the critical values for yielding. However, similarly to the stresses in the cover layers of the cone segment an increase of the stresses along

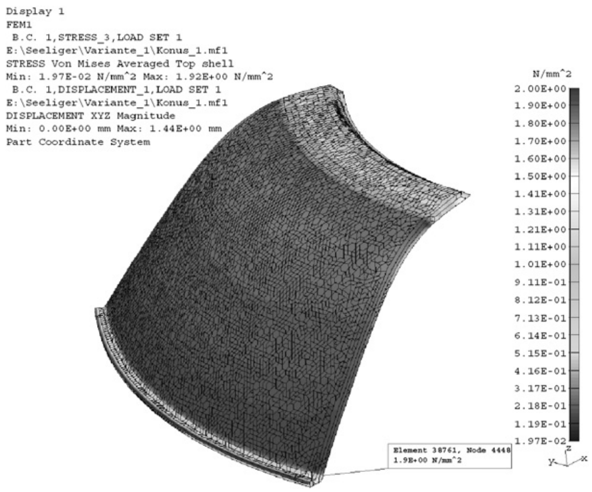

Fig. 5. von Mises stresses for the core layer.

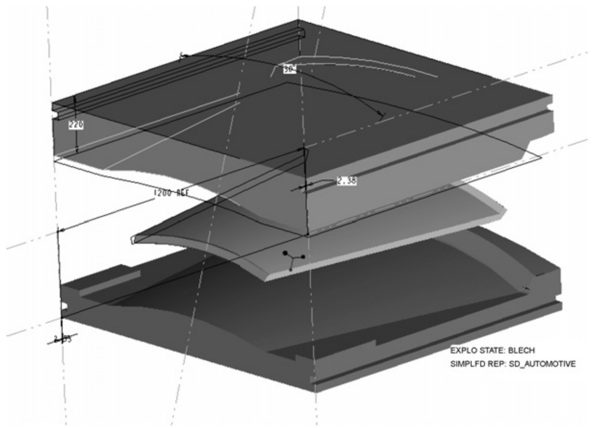

Fig. 6. Calibration tool with foamed cone segment therein.

the upper edge of the segments and in the flange was detected (Fig. 5).

5. Building of cone

The precursor material for the cone was manufactured according to the process described above. The so obtained sheets were laser cut to size of the cone segments.

Subsequently the sheets were brought to cone shape by roll bending.

Thereafter, the sheet was clamped in a steel tool and the flange of the segment formed by manual beading.

After foaming an additional step was applied, where the foamed AFS-segment was calibrated by means of a steel tool. As indicated in Fig. 6, the latter consisted of a lower and upper part where the foamed segment was placed in between and pressed to final shape.

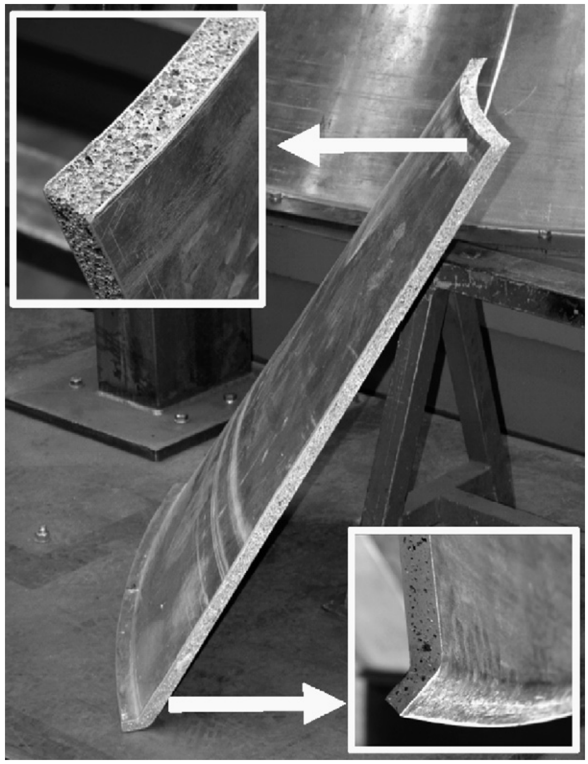

Fig. 7. Calibrated cone segment with details of flange and upper edge.

Fig. 8. Cone after assembly.

Fig. 7 shows a cone segment after cutting to final size.

The individual segments were joined by TIG welding of the cover layers. The upper ring was also TIG welded to the cover layers of the segments.

Fig. 9. AFS-cone on test jig, arrows indicating the effective direction of hydraulic actuators.

In order to strengthen the construction the weld seams joining the cone segments were covered by doublers that were also welded to the cover layers.

The final prototype of cone as shown in Fig. 8 has an upper diameter of 2.6 m, a lower diameter of 3.9 m and a height of 0.8 m at a weight of around 200–210 kg.

The AFS-segments alone have a weight of about 140 kg. They are quite representative of a flight structure.

The other areas of the prototype are not representative of a flight structure, for costs reason.

6. Testing of the cone

In order to test the cone and check whether the predictions from the calculations would describe the real behaviour, the cone was subject to a number of experiments. For this purpose the cone was fixed at its flange and a massive steel fixture attached to the upper ring in order to transfer the test loads to it. The steel fixture itself was loaded by means of hydraulic actuators (Fig. 9).

In a first step the cone was exposed to a vibration test. At this, the experimental results were more or less in accordance with the calculated ones for both axial and lateral vibrations.

During the following static tests, the cone was exposed to two different loading modes. In the first one, an axial force of 50% of the load indicated in specification DLA-NT-0-528-SDT–19/04/2001 was applied. In the second loading mode, this force was superimposed by a lateral force of 40% of the specification.

Measuring the displacements by means of a laser optical system the results obtained showed very good agreement with the theoretical data calculated in advance concerning the deformations.

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