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LIGHT-WEIGHT ALUMINIUM FOAM STRUCTURES FOR SHIPS

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Abstract
The possible application of light-weight structures based on aluminium foams for the hull and superstructure of ships was evaluated. For this aluminium foams were prepared using a powder metallurgical technology. Sandwich structures consisting of aluminium foam cores and aluminium face sheets were fabricated by adhesive bonding. Various fastening elements were applied to bare foam sheets as well as to the sandwich structures. Their strength was measured perpendicular to the sheet. Finally, the corrosion behaviour of light-weight aluminium foam samples in salt water was characterised.

Introduction

Metallic foams are now thought to be a useful and applicable material for industrial applications. Among the various available processes for making such foams [1-4] the method developed at Fraunhofer-Institute for Applied Materials Research (IFAM) in Bremen is one of the most promising ones. It has now become possible to obtain metallic foams of various metals and alloys in a fairly simple way. These foams enlarge the application range of cellular materials because of their excellent mechanical, thermal, electrical and other physical properties [5,6] as well as due to the fact that they are easier to recycle in comparison to polymeric foams. Parts of an almost arbitrary shape can be made by this foaming technique. Sandwich structures composed of a porous metallic foam core and metallic face sheets can also be produced with several options concerning material combinations and shapes.

Up to now the use of aluminium foams has only been evaluated for automotive and aerospace applications. In automotive industry, e.g., usage of large 3d-shaped sandwich panels serving as a replacement of conventional steel structures is discussed. IFAM has developed a sandwich in collaboration with the German car maker Karmann [7], which serves as the read seat wall and is ten times stiffer that the conventional part at slightly reduced weight. The development was driven by the requirement for increased passenger safety and the need for weight reduction in order to reduce fuel consumption.

In ships the need for new materials is different. Light-weight construction is also an important issue but other aspects gain importance as compared with the automotive sector. More flexibility of materials processing, e.g., is required because ships are not built with highly standardised parts but the material is processed during building. Corrosion behaviour is important both in cars and ships but the conditions are different. Finally, the size of the parts in ships is often very much larger so that the is a strong challenge for a new and more efficient production technology.

The present and still ongoing study was initiated by the German DOD and carried out in collaboration by Fraunhofer-Institute in Bremen (production of aluminium foams), Lürssen

Werft in Bremen (processing of foams into test samples) and WIWEB in Erding (testing of samples).

We report on first results of this programme comprising advances in the manufacture of aluminium foam sheets by means of a newly designed tool and testing of fastening elements. Moreover, some corrosion tests are presented. Finally, the further working programme and future tasks are outlined.

Sample Preparation

General description of the foaming technology

The production process begins with the mixing of metal powders - elementary metals, alloys or powder blends - with a foaming agent, after which the mix is compacted to yield a dense, semi-finished product (**Fig. 1**). In principle, the compaction can be done by any technique that ensures that the foaming agent is embedded into the metal matrix without any residual open porosity. Examples for such compaction methods are uniaxial compression, extrusion or powder rolling [8].

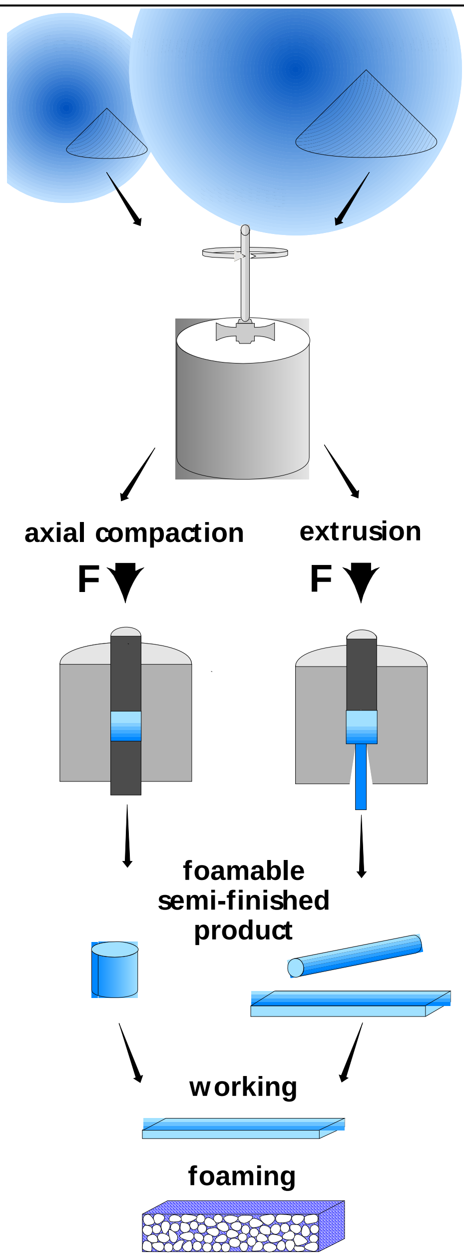

Figure 1: Fraunhofer P/M process

Heat treatment at temperatures near the melting point of the matrix material is the next step. During this process the foaming agent, which is homogeneously distributed within the dense metallic matrix, decomposes. The released gas forces the compacted P/M material to expand thus forming its highly porous structure.

Prior to foaming the precursor material can be processed into sheets, rods, profiles and other shapes etc. by conventional techniques like rolling, swaging or extrusion in order to improve the flow conditions during foaming inside moulds.

The density of metal foams can be controlled by adjusting the content of foaming agent and several other foaming parameters such as temperatures and heating rates. If metal hydrides are used as foaming agents, a content of less than 1% is sufficient in most cases.

Although most application ideas are based on aluminium foams, the Fraunhofer method is not restricted to this metal: tin, zinc, brass, lead, and some other metals and alloys can also be foamed by choosing appropriate foaming agents and process parameters. The most common alloys for foaming, however, are pure aluminium, 2xxx alloys and 6xxx alloys. Casting alloys, such as AlSi7 and AlSi12, are also frequently used because of their low melting point and good foaming properties, while in principle virtually any aluminium alloy can be foamed by properly adjusting the process parameters.

Fig. 2 shows a typical cross section of an aluminium foam. One sees that the distribution of cell sizes and shapes is random which is typical for a foaming process.

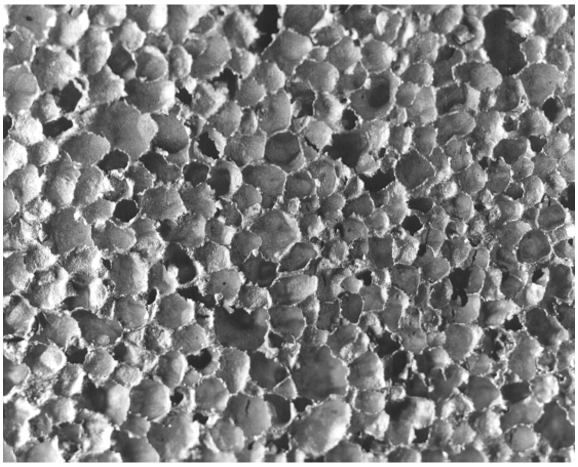

Figure 2: Optical micrograph of an aluminium foam (3:1)

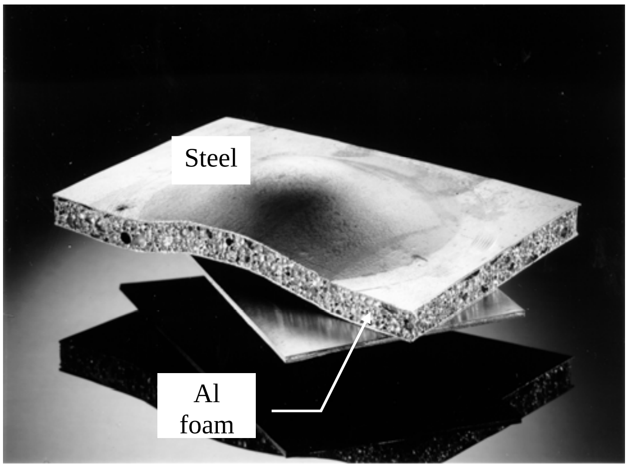

Figure 3: 3-d shaped sandwich panel. Face sheets: steel foam, core: aluminium. The roll-clad precursor can be seen beneath the sandwich.

Sandwich panels consisting of a foamed metal core and face sheets can be obtained by gluing the face sheets to a sheet of foam. Alternatively, if a pure metallic bonding is required, conventional sheets of metal - aluminium or steel - are roll clad to a sheet of foamable precursor material [9]. The resulting composite can be deformed in an optional step, e.g. by deep drawing. The final heat treatment then leads to a sandwich structure (**Fig. 3**).

Sample production for the tests

6061 alloy powder and TiH_2 as a foaming agent was used for all tests. 6061 alloys are known for their good corrosion behaviour and are easy to foam. The alloy powder was pre-compacted at room temperature to form billets for extrusion. The extrusion yielded bars of 200x20 mm cross-section which were further rolled to sheets of 3 mm thickness. These sheets were finally foamed to aluminium foam sheets of 10 mm thickness.

For the first tests samples of 200 x 200 mm size were produced. The density of the foams was between 0.6 and 0.65 g/cm^3. A tool was specially designed for the production of these samples. The tool consisted of two thin-walled steel sheets and a quadratic frame which could put together to form a mould of the desired geometry (**Fig. 4**).

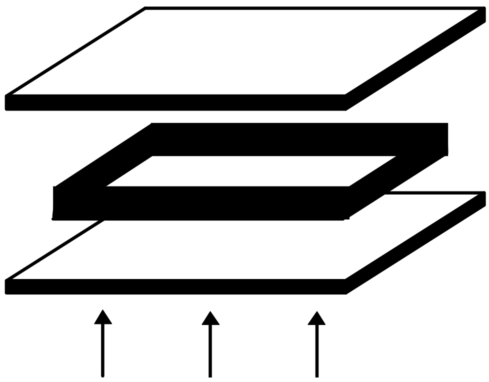

Figure 4: Mould used for making aluminium foam sheets (schematical sketch)

The mould was equipped with an array of thermocouples which allowed for a recording of the temperature profile during the entire foaming process. The mould was heated from beneath by three independent heating elements. The heating process was regulated by a computer-based control system which processed the input signals from the thermocouples and heated the mould appropriately. For foaming a piece of precursor material was inserted into the mould. As soon as the melting point of the alloy was reached, foaming started and the expanding foam filled the mould. After foaming the mould was opened and the foamed part removed.

Aluminium foam samples were investigated in various configurations as listed in **Tab. 1**. The face sheets were glued to the foam sheets under low loads using two different adhesives: an elastic polyurethane-based adhesive and a high strength epoxy resin adhesive.

Table 1: Configurations „aluminium foam/aluminium face sheets" used in the tests

	face sheets	no. of face sheets	adhesive used
1	none	-	-
2	0.8 mm AlMg3	2	PU-based adhesive Sikaflex 228
3	2.0 mm AlMg4.5Mn	2	PU-based adhesive Sikaflex 228
4	0.8 mm AlMg3	2	high strength epoxy resin adhesive
5	2.0 mm AlMg4.5Mn	2	high strength epoxy resin adhesive

Tests: Set-up and Results

Fastening elements

Various fastening elements were chosen for the tests. The choice was guided by the need to have fastening elements which can be applied „in situ" during the building of the ships superstructure. The elements given in **Tab. 2** were used. Note that not all combinations of fastening elements and aluminium foam structures could be realised due to limitations from the thickness of the face sheets or for other reasons.

Table 2: Fastening elements used for the tests

No	element	applied to
1	glued insert, 6 mm	all
2	tin screw, large	all
3	tin screw, small	all
4	pass through bolt, 8 mm	all
5	plined revet nut	all
6	iron angle, glued with Teroson	without face sheets and 0.8 mm
7	iron angle, glued with Sikaflex	without face sheets and 0.8 mm
8	aluminium disc, glued with Teroson	without face sheets and 0.8 mm
9	aluminium disc, glued with Sikaflex	without face sheets and 0.8 mm
10	iron angle, riveted	samples with face sheets only
11	thread bolt	2mm face sheets only
12	iron angle, welded on	2mm face sheets only

Some of the samples with various fastening elements can be seen in **Fig. 5.**

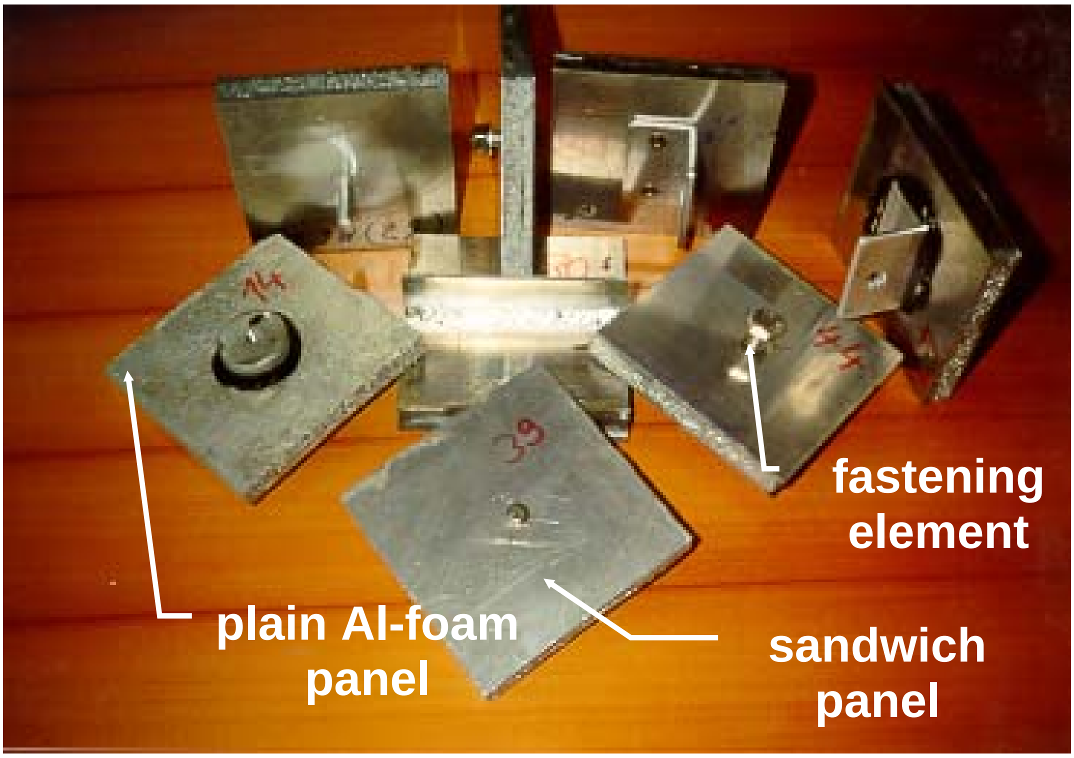

Figure 5: Aluminium foam samples with various fastening elements

The fastening elements were tested perpendicular to the sheet. Two samples for each configuration were tested. **Tab. 3** and **Fig. 6** show the results of the tests. For each test the maximum force is given. Tab. 3 gives the mean values of the two tests performed for each configuration, whereas Fig. 6 shows all data roughly in the order of falling strengths from left to right.

Table 3: Strength of fastening elements. Values given are in kN and are averaged over the two measurements. Figures printed in bold letters correspond to Fig. 7.

	Configuration				
	1	2	3	4	5
1	7629	**8029**	10063	12327	10910
2	1128	1118	2394	1830	3162
3	–	525	1408	1347	2494
4	5047	**8698**	16022	11802	20186
5	9855	829	4372	1749	4385
6	1609	7735	–	–	–
7	1248	–	–	–	–
8	1399	–	–	3912	–
9	1334	–	2193	–	–
10	–	539	3238	1766	4559
11	–	–	2470	–	1536
12	–	–	**7589**	–	–

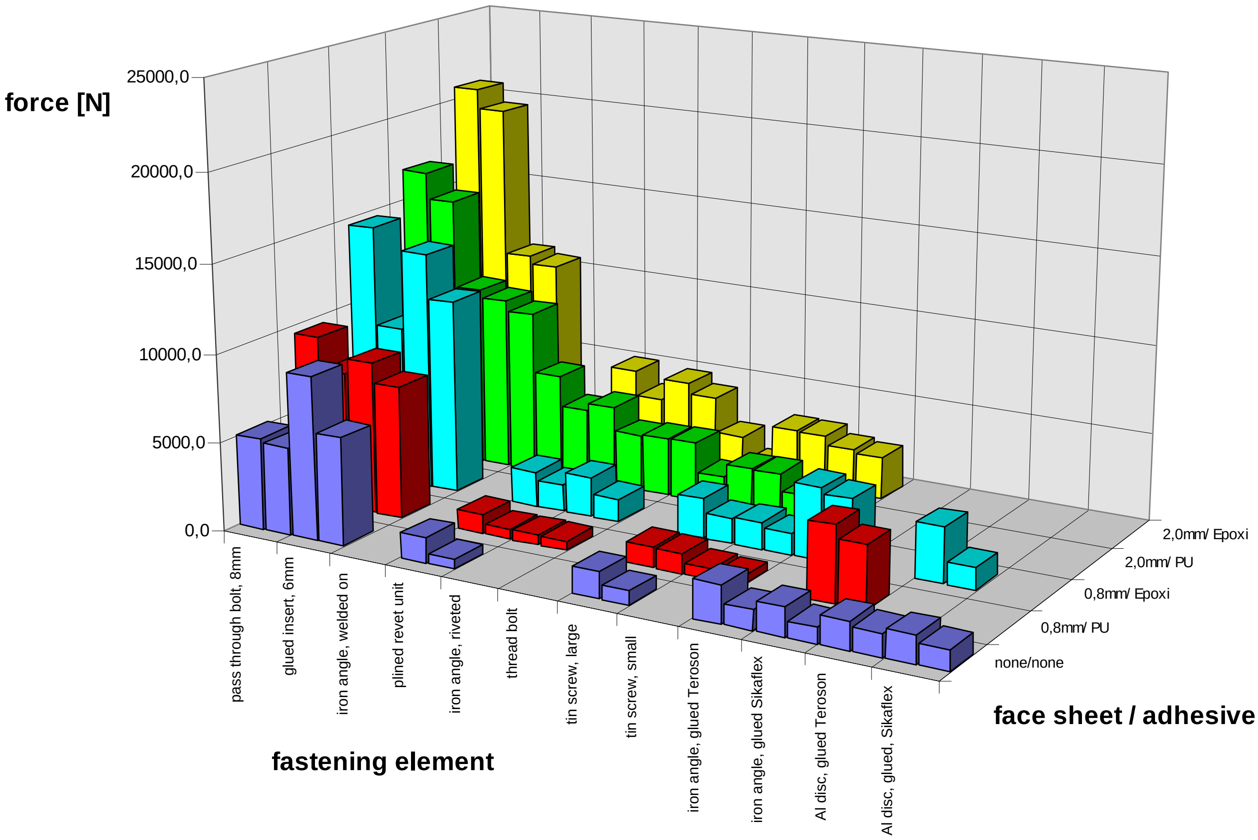

Figure 6: Strength of various fastening elements in aluminium foam samples

The failure mode was different for most samples. Some examples are shown in **Fig. 7**. In all cases the maximum force was between 7 and 9 kN.

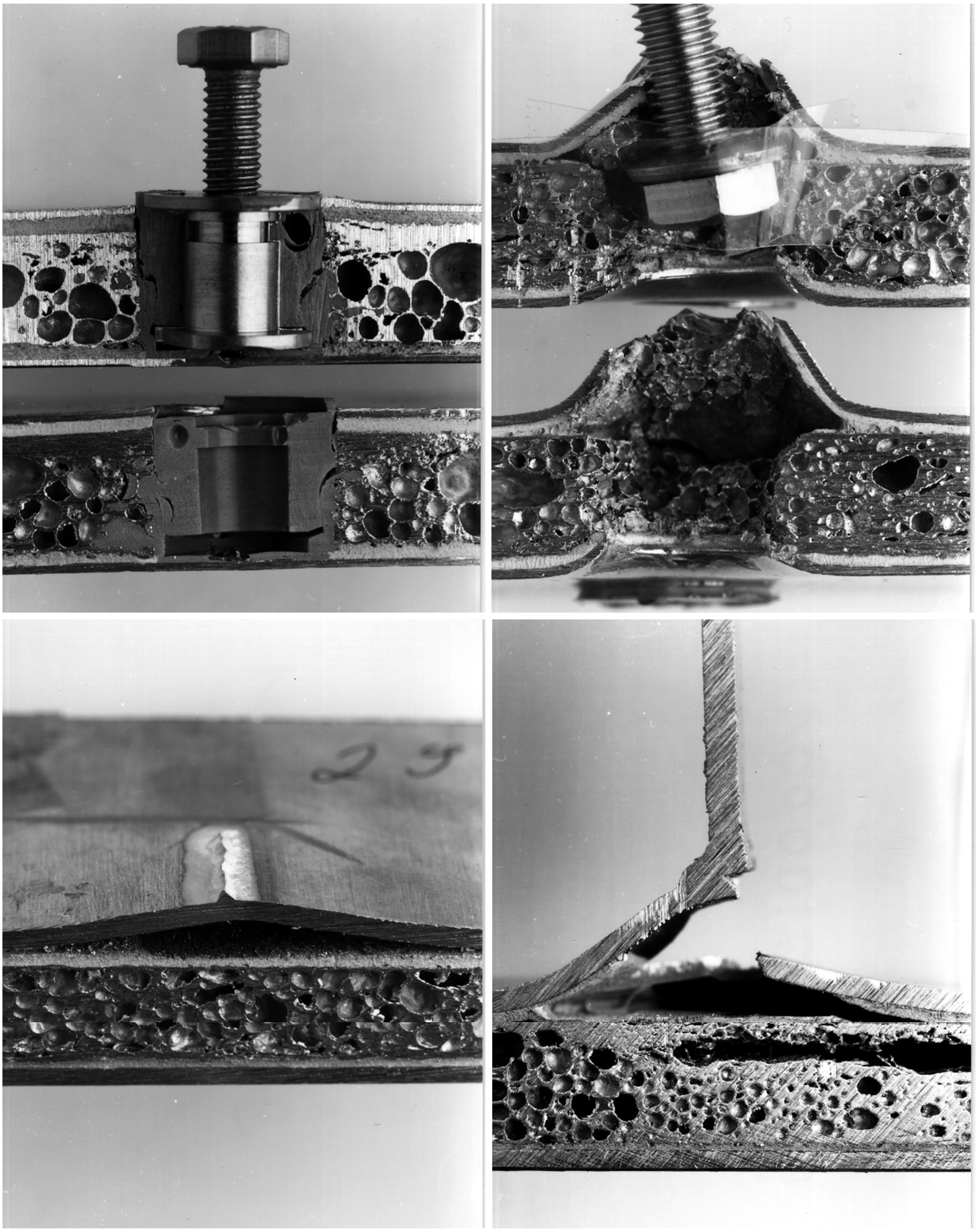

Figure 7: Aluminium foam samples with various fastening elements after testing. Upper part: face sheets 0.8 mm, PU-base adhesive in both cases, left:, glued insert M6; right: through bolt, M8; lower part: face sheets 2 mm and welded iron angle in both cases

Corrosion behaviour
Corrosion tests were performed on aluminium foam sheets with a closed surface. The samples were exposed to a sodium chloride spray (40g/cm^3) for 1000 hours at 25°C. **Fig. 8** shows one such sample after testing.

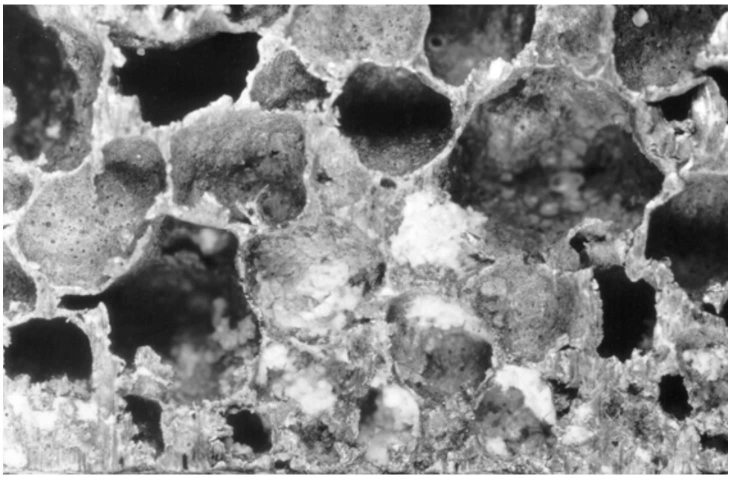

Figure 8: Aluminium foam sheet without face sheets after corrosion testing.

Discussion

Fastening elements
A variety of different fastening elements was tested. As can be seen from Fig. 6 the strengths are very different. The best results were obtained for the glued inserts and the through bolts, where forces up to 20000 could be applied. In these cases the strength increased from foams with no face sheets to foams with thick (2mm) face sheets. Moreover, the higher strength of the epoxy resin adhesive was an advantage as compared with the lower strength PU adhesive. As a first result it can be concluded that the fastening forces are both influenced by the thickness of the face sheets and the adhesive used.

Corrosion
Aluminium foams made by the powder metallurgical route show a surface which is almost closed. However, due to the degassing process during foaming some small perforations can not be avoided. Therefore, it is quite natural that some of the sodium chloride solution can enter the uppermost pore layer and eventually - provided that there is a certain interconnection between the pores - the next deeper layers. Fig. 8 clearly demonstrates that some of the pores are filled with sodium chloride, while others are empty.
The mechanical properties of corroded aluminium foams have not yet been tested. However, at the first appearance the foams seem to be quite unaffected by the corrosive medium. No structural defects were detected.

Summary and future work
Aluminium foams are being evaluated for their use in ship construction. In a first step fastening elements were tested. A first result was that the highest forces can be applied to aluminium foam/aluminium sandwiches which are bonded by a high strength adhesive and using fastening elements entering the sandwich. Fastening elements which were merely applied to the surface of the aluminium foam sandwiches or simple screws could mostly only

bear considerably lower loads. However, for many applications such strengths are sufficient so that there might be use for these types of fastening elements as well. Some corrosion tests were performed. The result was that some pores were filled with the sodium chloride solution whenever there were cracks or holes in the surface of the foam. No severe signs of corrosion were seen on the samples.

Future activities will include the possibilities of bonding aluminium foam panels to each other. Here various techniques will be investigated including adhesive bonding and welding. It will be important to identify techniques which can be used „in-situ“ during construction of the ship. An important issue which will be addressed in future work is the fatigue behaviour and shock resistance of aluminium foam sandwiches and in particular of the fastening elements and the fire resistance of such structures.

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