Adhesion in Sandwiches with Aluminum Foam Core

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Abstract

Fast-moving machine tool assemblies should be light and rigid. Because of the lightweight construction and the dynamic loads these assemblies are very often susceptible to vibrations.

Aluminum foam sandwiches are laminates with an aluminum foam core and compact cover sheets. The foam cores possess a high energy absorption capacity. Machine tool assemblies made of aluminum foam sandwiches offer very high flexural stiffness, together with comparatively light weight. Vibrations generated by machining are damped very well due to the cellular structure of foam.

The manufacturing process of foam sandwiches is in general well understood, but there are still some open questions concerning the mechanisms of bonding and adhesion between cover sheets and foam core. This paper tries to give answers to these questions.

Keywords: *Machine Tool, Aluminum Foam Sandwich, Adhesive Strength*

Lightweight Material Construction with Aluminum Foam in Machine Tool Manufacturing

Modern machine tool manufacturing is characterized by the demand for reduced primary and secondary processing time, together with constant or improved processing quality. Modern moving assemblies are susceptible to enormous accelerations. In high-speed machining, cutting speeds up to 10,000 m/min and rates of feed up to 40 m/min can be reached. For this, assemblies with optimized weight are required. In order to realize modern lightweight construction concepts under consideration of the required high machining precisions and high tool endurances materials with appropriate property combinations are required [1]. Aluminum foam combines low density with high stability; it shows a good mass/stiffness ratio, and due to its cellular structure it has high energy absorption and damping capacities [2]. Because of this diversity of properties aluminum foam offers excellent possibilities for making lightweight construction statically and dynamically stable [3, 4].

Usually, semi-finished aluminum foam products such as sandwiches and foamed profiles are produced, which can be easily assembled to large assemblies. Aluminum foam/steel sandwiches are capable to replace massive steel structures. Due to the high geometric moment of inertia, these composites possess a multiple of the flexural stiffness of steel sheets with equivalent mass [1].

Today, foaming procedure and manufacturing of semi-finished products such as sandwiches are well mastered. Many prototypes [1-5], and also serial assemblies [6] show the trend towards an intensive use of aluminum foam as material for lightweight material construction, either exclusively or in composites.

Besides sufficient availability and cost-effective production of aluminum foam/steel sandwiches, comprehensive knowledge on the properties of these composites is of basic importance for their use. In particular, the bonding between the composite components is fundamental. An important criterion in this context is the adhesive strength between the cover sheets and the foam.

Fabrication of Aluminum Foam/Steel Sandwiches

Basically, two ways of producing aluminum foam/steel sandwiches are used:

- Direct application of foam and thus bonding of the cover sheets;
- Gluing of the pre-fabricated foam core with the cover sheets.

The sandwich fabrication by direct foam application is realized in several process steps (fig. 1):

- Production of a mixture of the metal base powder (e.g. Al) and a foaming agent (e.g. TiH_2);
- Compacting the powder mixture, e.g. by the process steps of axial pressing and extrusion molding;
- Positioning and fixing the sandwich cover sheets in the foaming mould; depositing the foamable pre-material, and sealing the border areas;
- Foaming of the charged pre-material in the foaming mould at the melting temperature of the aluminum alloy, and subsequent cooling down.

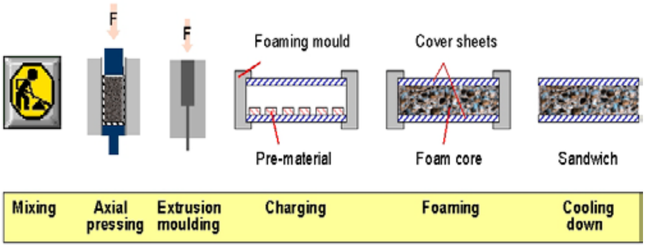

Fig. 1: Fabrication of aluminum foam/steel sandwiches by the melting powder metallurgical procedure

For technological reasons this procedure is especially appropriate for the fabrication of sandwiches with steel cover sheets. However, it is difficult to produce sandwiches with aluminum cover sheets because the external heat exposure usually causes the aluminum cover sheets to melt.

Possible Applications of Aluminum Foam/Steel Sandwiches

A composite of two steel cover sheets and an aluminum foam core combines low density (0.4-0.9 g/cm³) and the functional properties of aluminum foam with the good stability and elasticity properties of steel. The aluminum foam in the sandwiches serves as rigid, light and damping spacer.

For comparison, an aluminum foam/steel sandwich with 1 mm thick cover sheets and a foam height of 14 mm equals the flexural stiffness of a 10 mm steel plate in connection with a weight reduction by 65 %. When a steel plate and an aluminum foam/steel sandwich with equivalent mass are subject to a centered line load the steel plate will show a high deflection of 90 mm whereas the sandwich will show a deflection of 3.5 mm. That means that the sandwich has the 25-fold rigidity of the steel plate.

In order to fully employ the lightweight construction potential of aluminum foam the sandwich should have a definite ratio between the thickness of the cover sheets and that of the metal foam. The optimum for a sandwich with 1 mm thick steel cover plates and aluminum foam with a density of 0.6 g/cm³ is a sandwich height of 28 mm [7].

In principle, for the use of aluminum foam/steel sandwiches the following statements can be made:

- If existing steel walls of a structure are replaced by sandwiches of equal mass, the flexural stiffness is increased by a multiple of that of the solid steel wall;
- If sandwiches of equal flexural stiffness replace existing steel walls of a structure, the mass of the wall is reduced to a fraction of that of the solid steel wall.

The degree of change of the respective properties depends on the degree of geometric modifications.

Besides the multiple flexural stiffness of the aluminum foam/steel sandwiches in comparison to steel sheets with equivalent mass, the foam core is evident to be a vibration-damping element. The friction between the crack surfaces in the pore walls explains the good damping properties of the aluminum foam, i.e. they are caused by relative micromotions in the foam structure. Tab. 1 provides some values of the dynamic loss factor of common construction materials in comparison to that of aluminum foam [1, 4].

Gray cast iron	Steel	Reaction resin concrete	Aluminum foam
$1.44 \cdot 10^{-3}$	$0.74 \cdot 10^{-3}$	$6.4 \cdot 10^{-3}$	$4.5 \cdot 10^{-3}$

Tab. 1: Dynamic loss factors of different materials [4]

Example of Application

Aluminum foam/steel sandwiches are used today in numerous prototypes, and also in applications. These semi-finished products are not only appropriate for the use in fast moving machine tool assemblies but also for the construction of frames. The two portals of a milling machine for large tool manufacturing shown in fig. 2 are an impressive example for this. These portals have not been assembled as usual from steel plates but mostly from aluminum foam/steel sandwiches. In order to be able to realize such big assemblies, sandwich semi-finished products with about 1,200 x 1,200 mm^2 were pre-fabricated and assembled by welding to form the portals. As expected, the portals show a small deflection of 14 µm due to their own weight. The damping of the bending vibrations in x- and z-direction is between 2.3 and 2.9 % [1].

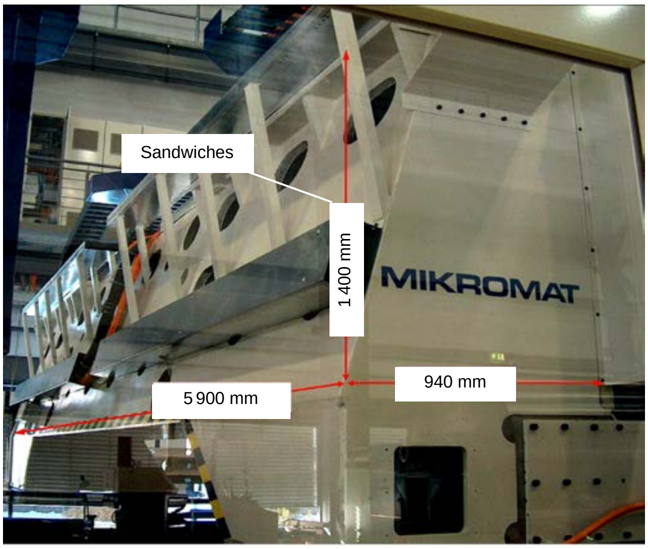

Fig. 2: A portal of a milling machine for large tool manufacturing made of aluminum foam/steel sandwiches

Adhesion Mechanisms

In aluminum foam/steel sandwiches the aluminum foam adheres to the cover sheets due to chemical adsorption, mechanical cramping and metallurgical interactions.

The bonding of atoms and molecules of similar or different type to solid bodies result from interactions of the outer electrons of the atomic shells (principal valence bonds), or by interactions of electrically polarized molecules (auxiliary valence bonds). In case of the principal valence bonds, also called primary valence bonds, one distinguishes between polar bonding, atomic bonding, and metallic bonding, but numerous hybrid forms are possible [8]. Aluminum foam/steel sandwiches are composites of metallic materials, therefore metallic bonding will dominate.

The mechanic clamping can be explained on the one hand by form fit of the molten aluminum foam with surface roughnesses of the steel cover sheets. On the other hand, the foam shrinks during the cooling process on the roughnesses resulting in a frictional connection. The proportion of the different working mechanisms to the adhesion process depends on the respective materials, the preparation of the surface, and on the process conditions.

In order to realize the adhesion processes during the fabrication of aluminum foam/steel sandwiches heat is required. The interatomic bonds are – similar to soldering – the result of four processes:

- Diffusion of atoms of the cover sheet material in the molten aluminum foam, leading to a solid solution during the subsequent crystallization process;
- Diffusion of atoms of the aluminum foam into the cover sheet, leading to a solid solution;
- Two-way diffusion of atoms of the aluminum foam and of the cover sheet material leading to intermetallic compounds;
- Adhesion (diffusion-free bonding) [9].

Adhesive Strength in Aluminum Foam/Steel Sandwiches

In the precedent sections it has already been shown that the adhesive force between the aluminum foam core and the cover sheets of a sandwich is of basic importance for the functioning of the assembly made of it (see introduction). That means that the minimum strengths must be reliably reached.

The bonding method is fundamental for the solidity of a composite. Aim of the following examinations was to determine the bond strengths of different sandwiches produced by gluing and direct application of foam (tab. 2). For this reason, the materials of the cover sheets and of the foam, as well as the foam densities and the surface properties of the cover sheets were varied. All sheets were cleaned and degreased before sandwich fabrication. Sheets thickness of the sandwiches with identification letter H was 1.5 mm, and that of the other sheets 1.0 mm. The alloys AlMg1Si0.5 and AlSi10, and the foaming agent TiH_2 have been used for the foam core.

Sandwich	Cover sheets	Treatment	Foam
Direct application of foam			
A 1	1.0330 (1)		AlMg1Si0.5
A 2	1.0330		AlSi10
B 1	1.0330	Etched	AlMg1Si0.5
B 2	1.0330		AlSi10
C 1	1.0330	Abrasive blasted	AlMg1Si0.5
C 2	1.0330		AlSi10
D 1	1.0330	Nickel electroplated	AlMg1Si0.5
D 2	1.0330		AlSi10
E 1	1.0330	Chemically nickel-plated	AlMg1Si0.5
E 2	1.0330		AlSi10
F 1	1.4016		AlMg1Si0.5
F 2	1.4016		AlSi10
G 1	1.4301		AlMg1Si0.5
G 2	1.4301		AlSi10
H 1	1.4713		AlMg1Si0.5
H 2	1.4713		AlSi10
I 1	1.4828		AlMg1Si0.5
I 2	1.4828		AlSi10
Gluing (1-component polyurethane glue ISOLEMI 50105 N)			
L 1	1.0330		AlMg1Si0.5
L 2	1.0330		AlSi10

Tab. 2: Examined sandwiches ((1) ... DC01)

For testing the adhesive forces in the composite, the drum peeling test according to DIN 53295 [10] has been chosen. With a tension testing machine the outer layer of a sandwich with constant radius was peeled off of the core and wrapped upon a cylindrical drum. The forces required for the peeling were measured and recorded. Before the test started a preload had been applied in order to adjust the peeling device. The peeling process took place with a pulling speed of the clamping device of 25 mm/min.

The samples have been prepared of foamed sandwiches with dimensions of 500 x 500 x 20 mm^3 (foam core approx. 18 mm), and foam densities between 0.5 and 0.8 g/cm^3. Of each sandwich, at least three samples were sawed out and prepared according to DIN 53295.

During the fabrication of the sandwiches for the peeling tests, the foamable pre-material was permanently in contact with the bottom cover sheet whereas the top cover sheet came in contact with the aluminum foam only after the expansion of the foam. Thus, the time of contact between the top cover sheet and the aluminum foam was shorter than that between the bottom cover sheet and the aluminum foam. For this reason, in the drum peeling tests always the top cover sheets were peeled off because this contact area constitutes the weakest link in the composite.

Fig. 3 and fig. 4 show that the highest peeling moments were determined for the sandwiches with direct application of foam having DC01 cover sheets (A to E). This statement is valid for both foam alloys. In general it can be stated that the peeling moments for the alloy AlMg1Si0.5 (e.g. A1) are a multiple of that for the alloy AlSi10 (e.g. A2). Furthermore, it can be seen that for both alloys the lowest peeling moments can be observed when high-grade steel is used as cover sheet (F to I). An exception was the combination of the ferritic, heat resistant high-grade steel 1.4713 and the alloy AlMg1Si0.5, for which high peeling moments were reached, too.

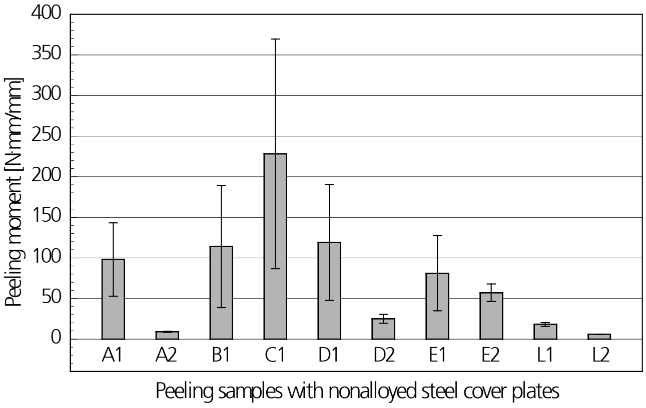

Fig 3: Peeling moments of sandwiches with nonalloyed steel cover sheets

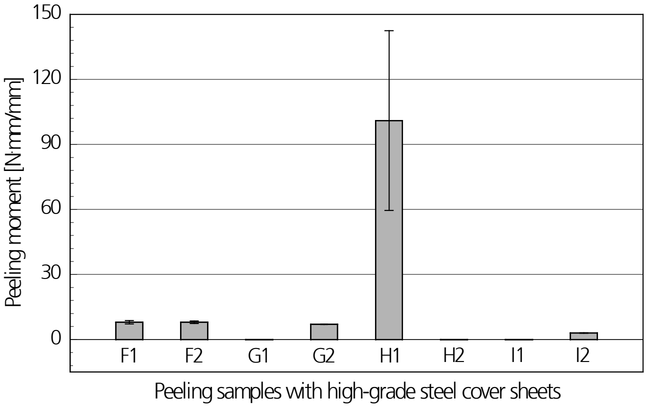

Fig. 4: Peeling moments of sandwiches with high-grade steel cover sheets

The highest peeling moments were determined for the sandwiches with abrasive blasted, pickled and nickel electroplated steel cover sheets, and with the alloy AlMg1Si0.5 (B1, C1, D1). The sandwiches with untreated or chemically nickel plated cover sheets, respectively, consisting of DC01 and a core layer of AlMg1Si0.5 showed slightly lower peeling moments.

For the alloy AlSi10, the highest peeling moments were attained in combination with chemically nickel-plated steel cover sheets.

Peeling samples with nickel-electroplated sheets show higher peeling moments than peeling samples with untreated cover sheets. In case of the sandwiches B2 and C2 with AlSi10 core, no adhesion or only a one-sided adhesion could be detected. Possible reasons for this behavior will be discussed below.

For the industrial application of sandwiches with aluminum foam core it is necessary to obtain adhesive forces above the strength of the aluminum foam. This condition will be fulfilled when in case of loading the foam will be destroyed and not the connection between cover sheet and foam core. According to the photos of the samples after the drum-peeling test (fig. 5) it can be seen that in case of the sandwiches with DC01 cover sheets or with cover sheets consisting of the high-grade steel 1.4713 and a foam core of the alloy AlMg1Si0.5 the foam structure has failed completely (D1, E1, H1) or partially (A1, B1, C1). The strength of the bonding was greater in these samples than that of the aluminum foam.

Fig. 5: Selected peeling samples after the peeling experiment (from left to right: A1, B1, C1, D1, E1, H1)

In all other sandwiches, the cover sheet was detached almost completely of the metal foam. Thus, these combinations failed in the boundary layer between cover sheet and metal foam and not as desired within the aluminum foam.

Due to the different densities in the peeling samples the determined peeling moments in dependence of the foam density were analyzed. Because for each test series only three samples have been investigated, conclusions will be limited only to trend correlations. In principle it can be assumed that for bad adhesion between foam and cover sheet no dependence between density and peeling moment exists – the peeling moment is small or even zero, and it is equal for different densities (e.g. F1, G1, I1, H2). However, in case of good adhesion such a dependence should exist. That means that during the peeling test the sheet will not be peeled off but the foam will be destroyed instead (fig. 6). Generally, and independently of the density, the peeling moments of sandwiches with AlSi10 core are distinctively below those of sandwiches with AlMg1Si0.5. The bad adhesion of the foam alloy AlSi10 in comparison to AlMg1Si0.5 can be explained by the high silicon content of this alloy.

Investigations on low-alloy steel [11] that had been immersed into molten aluminum revealed that already a silicon fraction of 2 percent in weight strongly inhibits the growth of the alloy layer. During the layer growth process silicon is embedded in the intermetallic phase thus slowing down the growth (fig. 7).

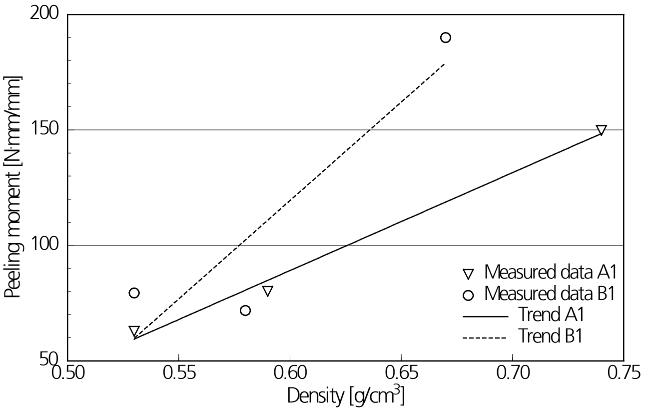

Fig. 6: Dependence of the peeling moment of the density of the foam core

The experiments revealed that foam cores of AlSi10 form good adhesion with the bottom cover sheet but only insufficent bonding or no bonding at all with the top cover sheet. That indicates that the foamable pre-material, which is in permanent contact with the bottom cover sheet, has sufficient time to establish good bonding with the steel sheet. However, the duration of contact between the foaming and molten aluminum with the top cover sheet is only short. Due to the fabrication of the sandwich is almost completed in the moment of contact, and the sandwich must be taken out of the heat treatment device and be cooled down. Owing to the high silicon content of the AlSi10 alloy the layer growth is decelerated, and so no bonding or only weak bonding is possible between the top cover sheet and the foam core (fig. 8).

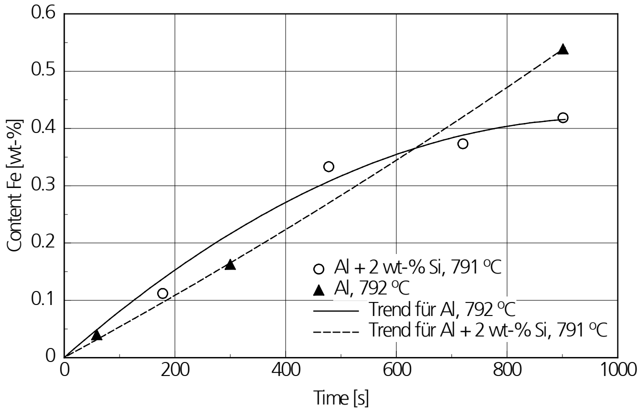

Fig. 7: Influence of the Si content on the iron concentration in molten aluminum [11]

As expected, this adhesion problem did not distinctly in the sandwiches with AlMg1Si0.5 core layer. By selecting an appropriate pre-material geometry offering good contact with both cover sheets during the whole foaming process this problem could be solved.

The corrosion resistance of high-grade steels is mainly caused by a concentration of the alloy element chromium of at least 12 %. The formation of chromium oxide on the steel surface leads to a passive state.

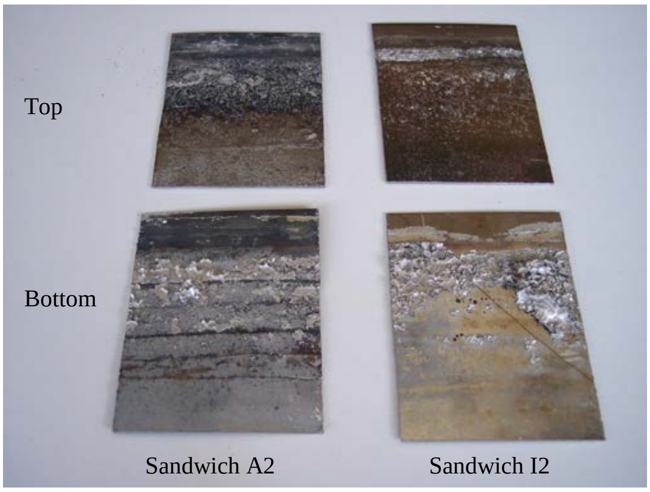

Fig. 8: Comparison of the adhesion of the AlSi10 alloy to the top (bad adhesion) and bottom sheets (good adhesion)

The high-grade steel 1.4713 is characterized by significantly lower chromium content with respect to the other high-grade steels. For this reason, the passivation layer is less distinctive than that of the other high-grade steels 1.4016, 1.4301, and 1.4828. Due to this less distinctive chromium oxide passivation layer, a better metallic bonding between the cover sheets and the aluminum foam can be expected. This assumption is confirmed by the results of the peeling tests.

In case of the glued samples (L) it can be determined that independent of the type of cover sheet, of the foam alloy, and of the foam density, and also independently of the applied adhesive, the bonding fails in the bonding zone. As expected, the glued peeling samples (L1) show distinctively lower peeling moments than the peeling samples fabricated by direct application of foam (A1), with steel cover sheets and AlMg1Si0.5 foam core. While the metallic bonding samples have an average peeling moment of 97 N·mm/mm, the glued samples only reach an average value of approximately 18 N·mm/mm. The comparably high variations of the peeling moments within one test series are surely due to the fact that during the expansion phase of the glue air inclusions occur leading to an inhomogeneous covering of the sheet with glue.

Adhesion Mechanisms in Aluminum Foam/Steel Sandwiches

In the literature [12] it is reported that in principle the formation of two types of boundary layers between the composite compounds are possible. Composition and structure of the boundary layer depend on the chosen core alloy and in particular on its silicon content. In alloys with silicon content below 1 %, the boundary layers consist of a binary iron aluminum phase. This applies for example to the alloy AlMg1Si0.5. Alloys with higher silicon content such as AlSi10 or AlSi12 develop a ternary system with additional aluminum fractions.

The binary boundary layer is normally composed of approx. 53 percent in weight of aluminum and 47 percent in weight of iron, and it is situated in the phase diagram between the brittle intermetallic phases Fe_2Al_5 and $FeAl_3$ (fig. 9).

The ternary boundary layer that is formed in case of core alloys with minimum silicon content of 3.5 % is composed of approx. 51 percent in weight of aluminum, 38 percent in weight of iron, and 11 percent in weight of silicon.

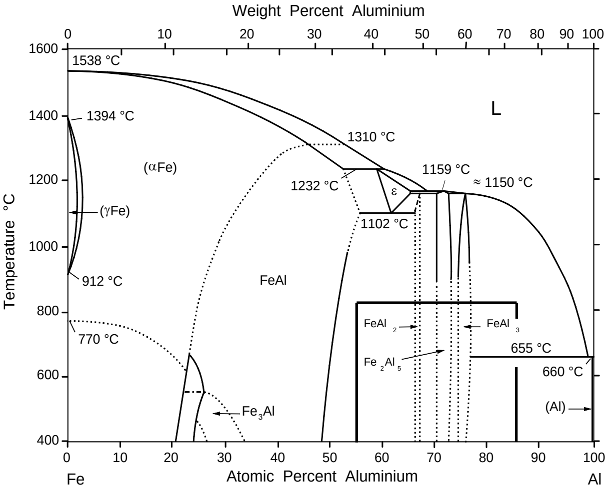

Fig. 9: Phase diagram Al-Fe [13]

In order to verify the theoretical facts, the boundary layers of selected samples have been analyzed by X-ray diffraction in order to do phase analysis. The diffraction angles were varied between 2ϑ □= 0° to 100° using Cu-K_α radiation. In this angle interval the most intensive peaks of the phases and elements to be considered were to be expected.

For the untreated and etched DC01 cover sheets, respectively, as expected the phase Al_5Fe_2 for the sandwiches with the alloy AlMg1Si0.5, and the phase Al_5FeSi for the sandwiches with the alloy AlSi10 as foam core could be detected. For both alloys, in the nickel electroplated cover sheets the phase Al_3Ni could be detected indicating bonding between the aluminum foam and the nickel layer of the cover sheet. In the samples with high-grade steel cover sheets, no distinct phase formation could be detected.

For a more precise characterization of the boundary layer between the steel sheet and the aluminum foam, and in order to verify the results of X-ray diffraction analysis, for certain samples an area analysis by the scanning electron microscope "LEO 1455 VP" was carried out using EDXS (tab. 3).

Sample	Al	Si	Fe	Ni
B1	56.4	1.3	42.2	0.0
D1	61.5	0.8	30.9	6.4
D2	67.4	14.9	3.5	13.0

Tab. 3: Chemical composition of the contact areas, percent in weight

Fig. 10 shows a micrograph of sample B1. The steel cover sheet, the AlMg1Si0.5 core, and also the transition layer can be seen clearly.

The analysis of the chemical composition of sample B1 confirms the results of X-ray diffraction analysis. The percentage distribution of aluminum and iron matches the phase Al_5Fe_2 detected by X-ray diffraction in good approximation.

In the samples with nickel-electroplated cover sheets (D1 and D2) aluminum could be detected with more than 60 percent in weight. Furthermore, in both boundary layers iron and nickel are present. The different percentages of these elements lead to the conclusion that the cover sheet of sample D1 had a much thinner nickel film than sample D2. This explains that in the X-ray diffraction diagram of sample D1 distinct iron peaks occurred in addition to the peaks of the phase Al_3Ni.

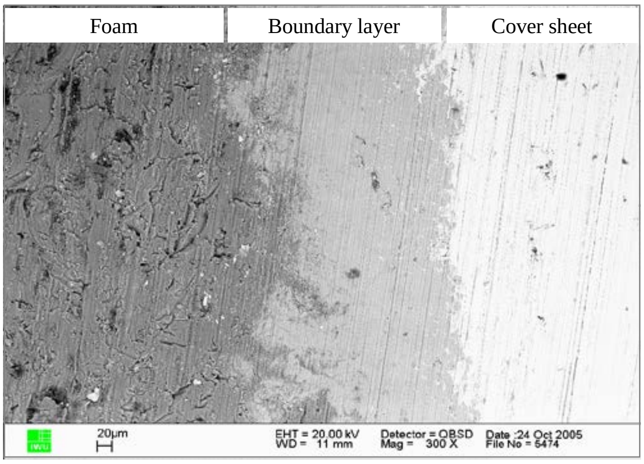

Fig. 10: SEM image of sample B1

Conclusion

Good adhesion between the cover sheets and the foam core is the crucial factor for the applications of the sandwiches. The adhesive force should be higher than the strength of the aluminum foam. With the help of drum peeling tests according to DIN 53295 the adhesion of different cover sheet/aluminum foam combinations has been analyzed. Good adhesion could be reached for sandwiches with cover sheets made of low-alloy steel, in connection with AlMg1Si0.5 core layers. Surface treatment such as blast cleaning or nickel electroplating leads to increased adhesion. Clearly worse results were obtained with the alloy AlSi10 and high-grade steel cover plates, except for the high-grade steel 1.4713 for which in combination with the alloy AlMg1Si0.5 good adhesion was obtained, too.

Glued aluminum foam composites were less resistant in comparison to metallically bonded sandwiches. In addition, all examined glue connections failed in the boundary zone between cover sheet and metal foam.

In order to characterize the boundary layer between aluminum foam and cover sheet selected samples were examined by X-ray diffraction analyses. The presence of the intermetallic phases Al_5Fe_2 and Al_5FeSi, respectively, in the boundary layers, known from the literature could be confirmed.

There is a large potential using aluminum foam/steel sandwiches in lightweight construction. Reproducible and high adhesive strength within compound structures is necessary for launching serial production of these semi-finished foam products. For the future there will be focus on pursuing analyses based on the present results.

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