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Aluminium foam–polymer composites: processing and characteristics

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Abstract Dissemination of closed cell metal foam unique properties (low density, efficient energy absorption, high vibration/sound attenuation) in real life products has often been difficult to realise. With advanced pore morphology (APM) aluminium foam–polymer hybrids a new and simplified process route targeted at application in foam-filled structures (e.g. automotive A-pillar) has been introduced. APM foams are made from spherical, small volume foam elements joined to each other in a separate process step. Joining the aluminium foam elements by adhesive bonding delivers composite foam with approximately 80–95 wt.% aluminium foam and 5–20 wt.% adhesive (polymer). Setting up cellular structures from spherical foam elements allows for automatic part production, good pore morphology control and cost effective aluminium foam application. An automated production line is displayed and discussed. Mechanical properties of APM aluminium foam–polymer hybrids are similar to other closed cell aluminium foams. Integration of APM foams in profiles resulted in significantly improved properties as observed for conventional closed cell aluminium foam fillings. The unique properties of APM composite foams make them an attractive alternative as a cost effective and easily applicable material of construction with targeted uses such as energy absorbing reinforcement of composite structures.

Introduction

Metal foams, re-invented in the early 1990s, e.g., by Baumeister [1], are on the way to being well understood and established material. Lightweight construction, energy absorption and vibration/noise attenuation are the main fields of application exploiting the combination of unique properties of the metal foam [2, 3].

In the European project “LISA” (5th European FWP “GROWTH”, GRD1-2000–25415) lightweight construction in combination with improved passive safety was the target for development of an aluminium foam-filled A-pillar (Fig. 1). This formerly hollow structure has been stabilised by local integration of an aluminium foam part. In a frontal crash test scenario the deformation pattern of the filled structure was similar to the original one. The aluminium foam core absorbed additional energy by plastic deformation and increased the deformation resistance of the steel panel structure. The energy absorption performance of the hybrid structure increased by approx. 40% compared to the original A-pillar. Required mechanical properties, geometry and position of the aluminium foam insert were found by iterative virtual optimisation. Insertion of the foam core into the A-pillar structure took place at the original automotive body structure production line. All foam-filled A-pillars went through the anti-corrosion protection processes. The production tests prove that this composite foam system is compatible with existing production lines, and the process is mature enough for large scale processes needed in the automotive industry [4].

The cellular structure of metal foam also attenuates vibration and noise. Equipping a steel gear wheel with aluminium foam components (Fig. 2) reduces noise emission up to 10 dB (A) at full transmission of torque and turning speed as compared to an all steel reference part. Further, the weight of the gear wheels is lowered 25%. A part of the dense steel volume is replaced by lightweight aluminium foam [5].

Analysing (potential and already established) applications for closed cell aluminium foams revealed, in many

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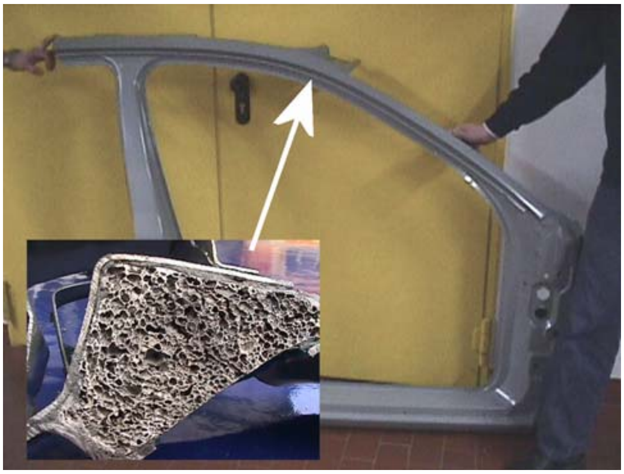


Fig. 1 Automotive A-pillar reinforced by local aluminium foam insertion

Fig. 2 Hybrid gear wheel with aluminium foam component

cases, that cellular metals are combined with other dense materials. Low Young's modulus and tensile strength of aluminium foams require hybrid design with dense components bearing high static and dynamic loads.

Near-net shape aluminium foam part production

Shaped aluminium foam parts are made by expansion of foamable precursor in temperature-resistant foaming moulds, e.g., made of cast iron (Fig. 1, left).

The precursor-filled mould is heated in a furnace until the expansion process starts with melting of the metal. The foaming agent decomposes and releases gas (e.g. H_2) which expands the liquid metal into cellular (still liquid) metal foam. The expanding foam reproduces the inner contour of the mould resulting in a near-net shape aluminium foam part with closed surface skin (Fig. 3, right). As soon as the mould is completely filled, it is taken out of the furnace (heated zone) to cool and freeze the liquid metal foam into the solid state.

Near-net shape aluminium foam part production in moulds requires insight into the foam expansion process. Homogeneous heat transfer into the precursor and, after foam expansion, from the liquid foam (for freezing to solid state) is most important for high quality parts with homogeneous as well as reproducible pore morphologies. A simple example demonstrates the difficulty of achieving a homogeneous heat transfer. Assume a cylindrical precursor rod in a mould with cuboid inner cavity is heated in a chamber furnace. Heat is transferred via the moulds surface through the precursor rods surface into the precursor volume. The middle of the precursor rod is heated only via the peripheral surface. The ends receive additional heat through their front surfaces. At high heating rates conductivity of the precursor material is not sufficient to homogenise the temperature in the rod. Ends start foam expansion before the middle section (Fig. 4). This inhomogeneous foam expansion results in pore morphologies with gradients in pore size and distribution [6].

Foaming mould design, heating/cooling temperature profile, precursor geometry and its position in the mould need to be optimised for each individual foam part. The first serial production of aluminium foam energy absorbers

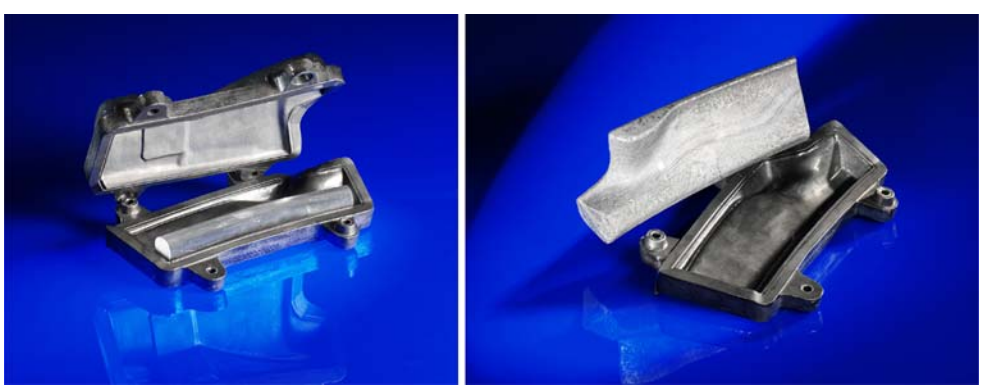


Fig. 3 Near-net shape aluminium foam part production by expansion of foamable precursor material in temperature resistant foaming moulds, e.g., made of cast iron (left: precursor rod in open mould; right: finished aluminium foam part and bottom mould halve)

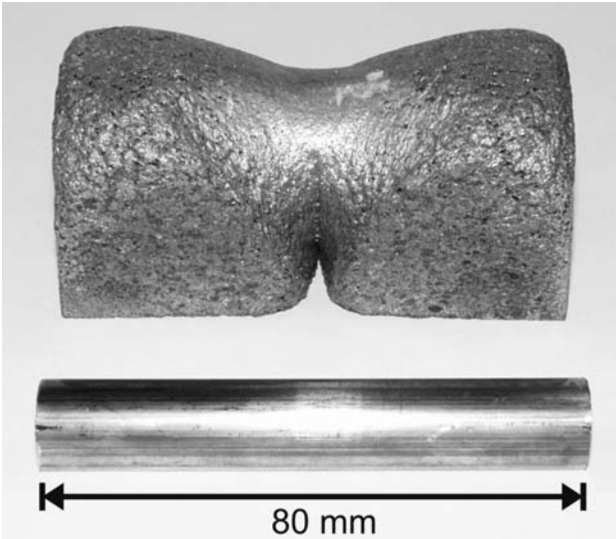


Fig. 4 Example of inhomogeneous foam expansion due to inhomogeneous heat transfer into precursor material (top: foam part; bottom: precursor rod)

for automotive application showed that near-net shape foam part production in moulds is mature to fulfil automotive industry's high quality requirements and ambitious cost targets [7].

Technology concept of aluminium foam–polymer hybrids

Analysing near-net shape production of closed cell aluminium foam parts in moulds showed that the combination of heat driven foam expansion and complex heat transfer through the mould requires specific insight and complex process management. Once established, this process route is economic for high output serial production of identical geometry foam parts. In this case near-net shape part production reduces post-processing, which compensates for the cost of the foaming moulds. For small and medium sized part numbers the individual foaming moulds are significant cost drivers. Further, any subsequent change in part geometry would require new foaming moulds and process management adaptations.

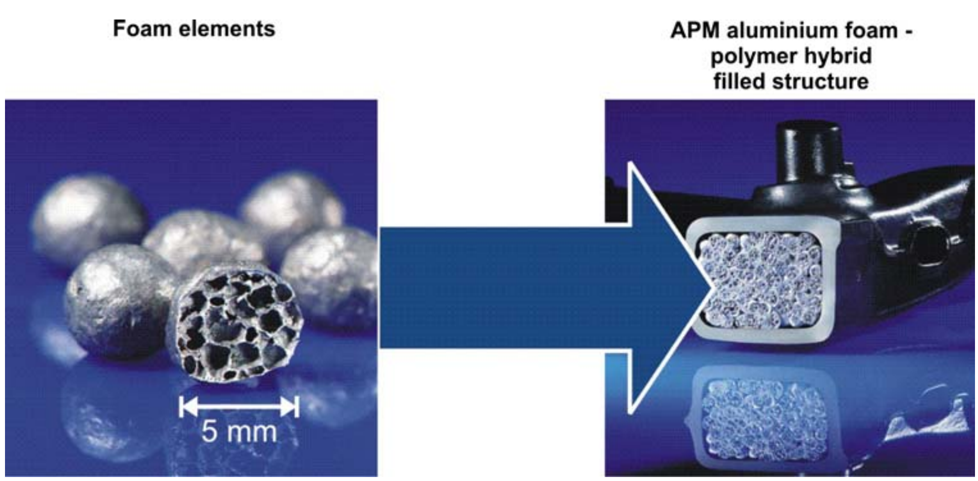
Taking into account that aluminium foam parts are often integrated as lightweight cores into hybrid structures by adhesive bonding it is questioned if near-net shape foam part production in moulds is the most effective processing route. With the advanced pore morphology (APM) aluminium foam–polymer hybrids a simplified and more flexible process alternative has been developed. The foam component in a hybrid structure is set-up from numerous small volume and standard geometry foam elements directly joined (e.g. adhesive bonding) in the structure (Fig. 5).

The aluminium foam elements are produced without a mould. Small volume precursor granules expand into spherical foam elements. Surface tension of the metal melt shapes the elements spherical. Figure 6 illustrates expansion of a cuboid precursor granule and the transition into a spherical foam element. Due to gravity force the geometry is not perfectly spherical but ellipsoid comparable to a water drop on a flat surface [6].

In contrast to foam expansion in moulds, the heat from the furnace flows directly into the precursor and is not retarded by the mould. The expansion process time is reduced. No energy is wasted for heating and cooling of the mould material. Thus, heat flow into the precursor granules as well as from the expanded foam element is simple to control due to the simple precursor and foam element geometry. The result is a high reproducibility of the expansion level and the foam density.

After expansion these foam elements are coated with a thermoplastic polymer/adhesive (e.g. Polyamide 12), which is non-tacky at room temperature. The coated foam elements can directly be poured into the hybrid structure

Fig. 5 Concept of advanced pore morphology (APM) aluminium foam–polymer hybrids



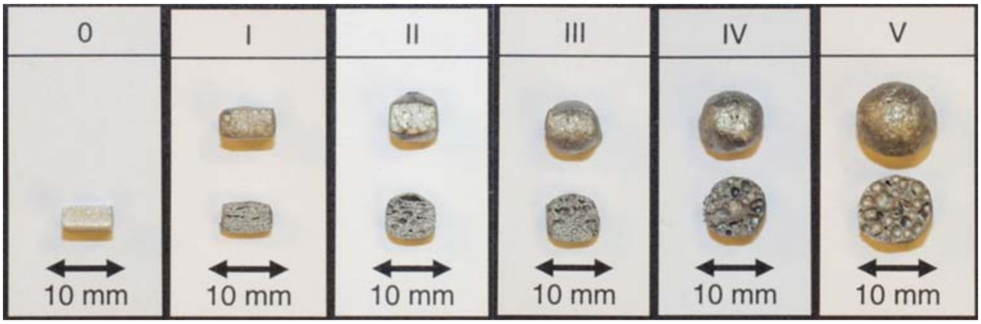


Fig. 6 Expansion states of a cuboid foamable precursor granule (top: side view; bottom: cross section)

without agglomeration. Subsequent low temperature (usually <200 °C) heat treatment melts/activates the adhesive coating on the foam elements. The coatings of the neighbouring elements merge and also adhere to the surrounding structure where in contact (Fig. 7). Due to the set-up from spherical elements, APM aluminium foam–polymer hybrids have approximately 40% open interstitial porosity. The hybrid material consists of approx. 80–95 wt.% aluminium foam and 5–20 wt.% adhesive (polymer).

The joining process is accompanied by shrinkage of the APM foam volume compared to the volume of the loose foam element bulk (up to 10% in this study). Modelling APM foam with the cubic arrangement of ideal spheres strongly abstracts the actual random close-packed element arrangement but is sufficient for estimation of shrinkage (displayed in Fig. 8). As soon as the polymer coating is liquefied the rigid aluminium foam elements displace the liquid coating at contact points due to gravity. The effective diameter of the coated elements is reduced. The total APM foam volume shrinks. This shrinkage ε_0 can be estimated from the element diameter D and the adhesive coating thickness b (Eq. 1). Experimental tests proved sufficient accuracy of Eq. 1 [6].

$$\varepsilon_0 = \frac{2 \times b}{D + (2 \times b)} \tag{1}$$

The described shrinkage needs to be taken into account during production of APM foam filled structures. Shrinkage of the APM foam filling during activation of the adhesive might lead to gaps or incomplete cavity filling. This loss in APM foam volume needs to be compensated by surplus filling. Complex cavity shapes and undercuts require local supplementary foam element feeding during the joining process step.

Fig. 7 Opened extrusion profile with APM aluminium foam–polymer hybrid filling (front: single foam elements including cross sectional view)

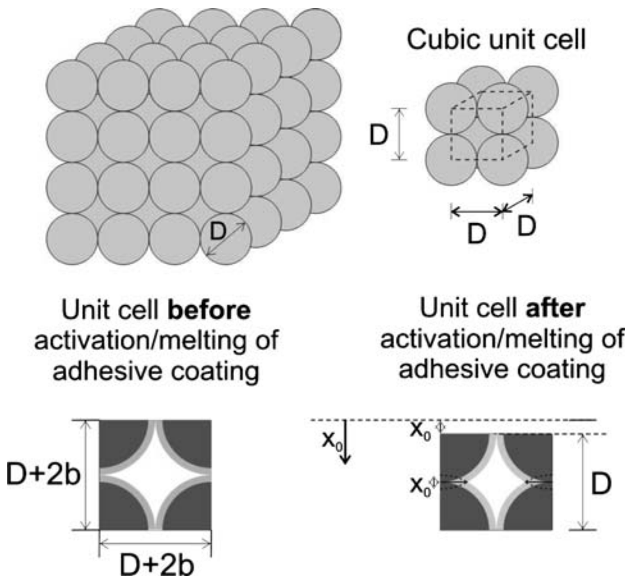


Fig. 8 Schematic illustration of APM aluminium foam–polymer hybrids and its shrinkage during activation of the adhesive coating on the aluminium foam elements

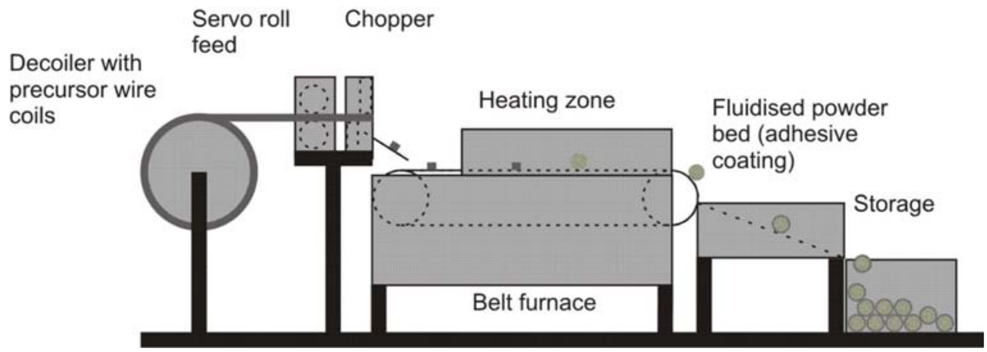


Fig. 9 Semi-automatic production line for adhesive coated APM aluminium foam elements

Automated production

As basis for mass production of APM aluminium foam–polymer hybrids an automatic production line for expansion and coating of foam elements (Fig. 9) has been developed and implemented. The starting materials (aluminium alloy powder, foaming agent powder) are homogeneously mixed and consolidated into wires (e.g. diameter = 3 mm) by continuous powder compaction (CONFORM process) [7]. These wires are cut in foamable precursor granules (e.g. length 2 mm), which are subsequently expanded into spherical foam elements in a conventional belt furnace. Directly after expansion the still hot foam elements are coated with thermoplastic adhesive in a liquidised powder bed coater. Charging into the structure to be equipped with APM foam is done with established bulk material handling equipment.

Properties

Mechanical testing of APM aluminium foam–polymer hybrids showed no major differences to near-net shape produced foam samples (Fig. 10).

Only at low compressive strains (<15%) the elemental set-up and the additional open (interstitial) porosity in APM samples cause a smoother transition from quasi elastic to plastic deformation and a lower stress level. With increasing compression of the open porosity the compressive stress versus strain curves of both sample types converge. Main parameters influencing the mechanical properties are the aluminium foam elements density and matrix alloy as well as the adhesive properties and coating thickness.

The APM technology concept has been developed for foam application as filler material in hybrid structures. Uniaxial compression testing of APM foam-filled square cross section aluminium extrusions showed the filling's impact on the deformation pattern of the profile. The original extrusion develops two folds corresponding with two maxima in the compressive force versus strain curvature

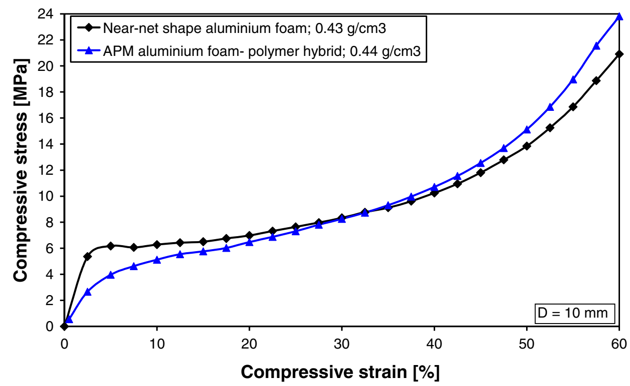


Fig. 10 Compressive stress versus strain in uni-axial compression of APM aluminium foam–polymer hybrid and near-net shape aluminium foam samples of equal density

(Fig. 11). With the APM foam filling inward folding of the profile is inhibited. The folding length decreases and the number of folds increases to three resulting in a significantly higher force level. This so-called interaction effect is known for other closed cell aluminium foam fillings in extrusion profiles [8] and is not unique to APM aluminium foam–polymer fillings.

Conclusions

Application fields for closed cell aluminium foams are, e.g., lightweight construction, energy absorption management and noise and vibration attenuation. Due to their specific properties they are often applied as one component in hybrid structures with other dense materials. Combination of different material property portfolios results in superior performance of the composite part.

Near-net shape production of aluminium foam parts in moulds is an established processing route for serial mass production. Costs for high temperature resistant moulds as well as complex process (heat flow) management are compensated by avoidance of post-processing the final foam part.

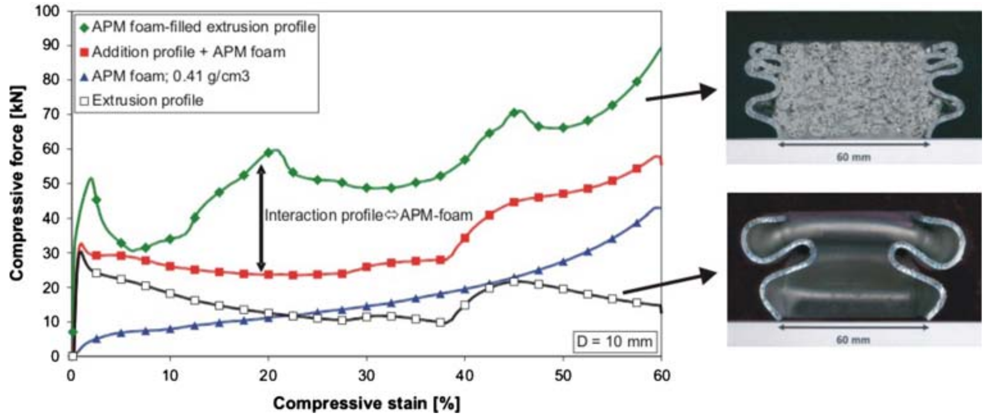


Fig. 11 Aluminium extrusions without and with APM aluminium foam–polymer filling in uni-axial compression testing

The target to reduce the complexity of aluminium foam production and application for enhancement of market penetration led to the alternative advanced pore morphology (APM) technology concept. Reducing the foam geometry to simple spherical shape avoided moulds, increased the process energy efficiency and simplified process control as well as automation. Direct APM part shaping in the later hybrid structure requires a prepared cavity but also provides maximum flexibility in terms of geometry changes. In near-net shape processing a new part design requires a new foaming mould and process adaptations. For APM foam fillings just the charging volume needs to be adjusted. Consequently the end-user is able to produce any aluminium foam part shape without specific foam expansion know-how.

Adhesive bonding the foam elements to each other and the surrounding structure allows for further process integration into existing production lines. E.g. in automotive body structure corrosion protection processing several low temperature heat treatments (drying/curing operations) could also be used for activation/melting of the adhesive coating on the foam elements. Currently running research activities are focussed on full integration and maximum compatibility with automotive production lines.

Finally mechanical testing of APM aluminium foam–polymer hybrids and filled structures showed no major difference to existing closed cell aluminium foams and their role in hybrid structures.

The initial target to simplify and automate integration of aluminium foam unique property portfolio into structural components has been achieved by the advanced pore morphology (APM) processing route.

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