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DEVELOPMENT TREND OF ADHESIVE JOINING OF ALUMINIUM FOAMS

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Abstract
Aluminium foams structures, due to its impact absorbing properties could be considered as passive safety systems in transportations which still have a great potential for development as a way to reduce deaths and injuries, which is also associated to the economic costs and social impacts associated with this problem. On the other hand, from an environmental standpoint, the use of advanced composite materials to this end can also represent an optimized level of energy efficiency. The impact energy absorption, with the use of a well-designed lightweight protection system, is directly related to the thermal efficiency and consumption of the engines, thus leading to a lower level of greenhouse gases sent to the atmosphere. Without developing manufacturing technologies, it can not be possible, that is why the joint technology should adapt to the recent, combinations of materials. The connection between aluminium foam to aluminium foam design is one way for the bonding established by adhesives. In this paper adhesive joining of aluminium foams were investigated for the base of a further research project.

1 Introduction

1.1 Global development trends in the vehicle industry

The automotive industry has certainly begun to show signs of rebounding from the economic downturn; however, companies are now being asked to “do more with less” as production volumes approach the levels of several years ago. More than ever, companies require operational efficiencies to maintain process flow and avoid unscheduled downtime of automated equipment. Over the decades, harmful vehicular emissions have shown a negative impact on the environment and human health. The increasing air pollution from the transportation sector has led many government agencies to lay strict regulations on the automobile manufacturers to curb the harmful emissions under permissible limit [1].

One such example is the European agency, which has set mandatory emission reduction targets for automakers in Europe. According to EU rules, the fleet average by cars to be achieved by 2021 must be 95 grams of CO2/kilometer, which works out to a fuel consumption rate of around 4.1 liter/100 km of petrol or 3.6 liter/100 km of diesel [2]. Stringent regulations and heavy penalties imposed by government agencies have put immense pressure on automakers to scout different methods and technologies that help curb vehicular emissions [3].

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The manufacturers are using different types of steels in the body, depending on what the function of the structural element. The following figure shows a recent motor-vehicle body with the used types of steels and their integration spots (*Figure 1*).

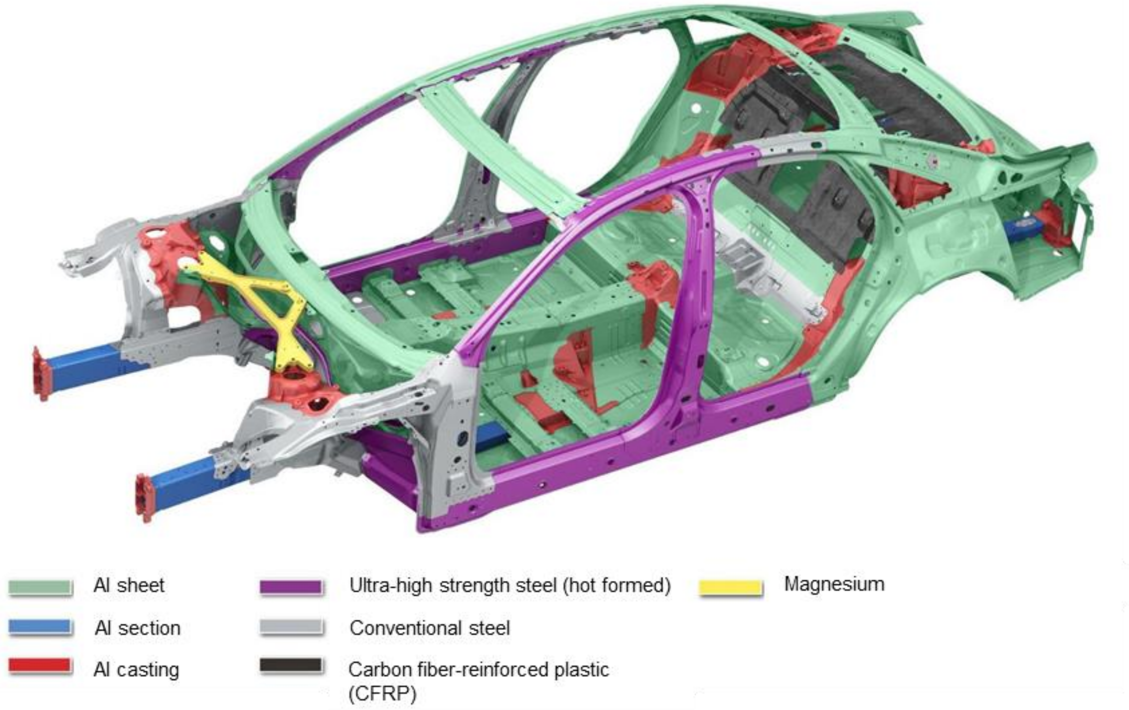

Figure 1. Different parts of of Audi A8 body [4]

The different color shows the type of the metals in the vehicle body. Where they need higher strength and stiffness, because of the safety, they use high ultimate strength steels. In case of accident, where the deformation and the energy absorption is the important, they use lower strength, generally used non-alloyed DC steels [5]. The most of the body contains aluminium sheets, with this the weight can be reduced, with the same strength of the body.

1.2 Aluminium foams in the vehicle body

Composite and foam materials have begun to replace traditional materials because of the necessity for a more economical use of energy. Metal foams can be used in a wide range of fields from mechanical to thermal applications thanks to their superb strength/weight ratios.

Metal foams offer unique physical and mechanical combinations such as high resistance and lower specific gravities or high gas permeability and superior thermal conduction. Despite the many advantages features of metal foams for using in industry must have the appropriate assembly techniques. Research of foam materials are generally limited to production of foam, studies on secondary operations of foam are insufficient [6].

Metal foam is cellular material as wood, so they can be joined with techniques for developed woods joining such as wood screws, adhesive joints and embedded links. Also using joining techniques of metals is possible for metal foams [6-8].

Metal foams have properties which make them attractive in light-weight construction, for energy absorption devices and for acoustic or thermal control. All these fields are relevant for automotive industry, which has been extremely interested in them since they were first developed. Potential applications also exist in ship building, aerospace industry and civil engineering [6,7].

Light-weight construction: foams can be used to optimize the weight-specific bending stiffness of engineering components. For example, the bending stiffness of flat foam panels of a given weight, width and length is approximately proportional to their thickness, and therefore inversely related to density. True optimization, however, calls for more elaborate solutions as will be discussed below.

In any case, light-weight construction exploits the quasi-elastic and reversible part of the load-deformation curve [9].

Energy absorption: owing to their high porosity, foams can absorb a large quantity of mechanical energy when they are deformed, while stresses are limited to the compression strength of the material. Foams can therefore act as impact energy absorbers which limit accelerations in crash situations. This mode exploits the horizontal, irreversible part of the load-deformation diagram. As metal foams can have much higher collapse strengths than polymer-based foams – up to 20 MPa – they can find applications in areas not accessible to foams up to date [10].

Acoustic and thermal control: foams can damp vibrations and absorb sound under certain conditions. Moreover, their thermal conductivity is low. These properties are not outstanding – polymer foams are much better sound absorbers – but they could be useful in combination with other features of the foam. This application makes use of the internal configuration of a foam, namely the labyrinth of struts and the associated air-filled voids [11].

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 [12].

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 [13].

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 (*Figure 5*) [12].

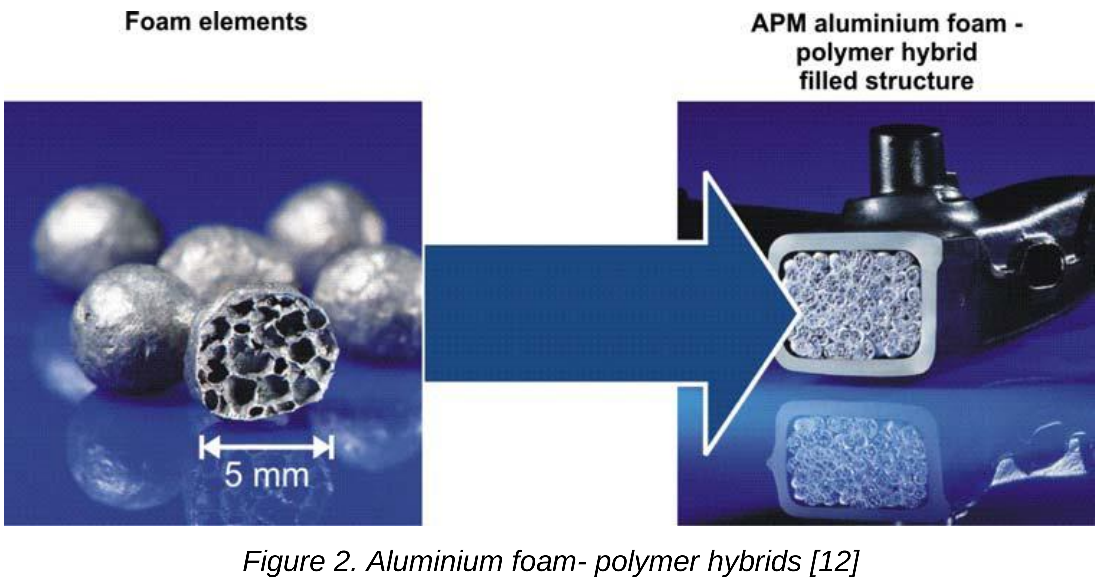

Figure 2. Aluminium foam- polymer hybrids [12]

Aluminium Foam Sandwich (AFS) is a product comprising a highly porous aluminium alloy foam core and two aluminium alloy face sheets. The layers are firmly attached to each other by metallic bonding. Use of such sandwich panels has been proposed for many industrial sectors including automotive [6, 13], ship building [14], railway and aircraft industry [15].
Although increasing strength reduces the malleability of the materials. However, malleability is one of the key issues of manufacturing body components, so common use of basic, increased strength steels and aluminium is necessary. Without developing manufacturing technologies, it can not be possible, that is why the joint technology should adapt to the recent, hybrid combinations of materials.
The aluminium foams can be connected useing self-piercing rivet, bolt, clinching and welding, but an innovative technology could be if we joint the foam parts with adhesives.

1.3 The importance of wetting in the joint technologies

Wetting, in general, is the interaction of a liquid phase with a solid phase when surrounded by a gas phase or a second liquid phase. There are many common examples of wetting phenomena, such as the spreading of a liquid over a surface. The interfaces which are produced can be solid/liquid, solid/gas or solid/liquid, liquid/gas or liquid/liquid. Wettability is most often described by the geometry of a sessile or resting drop [16]. Contact angle (θ) is a measure of wettability and is defined as the angle between the surfaces of the liquid and the solid substrate at the line of contact, as measured from the side of the liquid. A low contact angle means high wettability and a high contact angle means poor wettability. Wetting behaviors are important in the vehicle industry and the development [17]. A lot of paper deals with the modification of surface properties to increase the surface energy (decrease the contact angle to the way of hydrophilic), with these techniques the quality of the joints can be improved. The surface modification could be a laser beam treatment [18]. In this study the contact angle represent the quality of the connection between the two alumunium foams.

1.4 Adhesive bonding of aluminium foam to aluminium foam

Adhesive bonding is the process of binding two components using a suitable binder (i.e. an adhesive). Applications of adhesives for joining elements made of dissimilar materials are commonly employed in aviation, automotive and building industries [19]. Joining of CFRPs with aluminium alloys via adhesive bonding is by far the most conventional method with both advantages and limitations, The investigated researches used, CFRP with aluminium, but we could use these experiments to joining aluminium foams with adhesives. Since adhesive bonding is an irreversible process, attempts to dissemble the joints can be expensive, which results in the complete material damage involved in the joints.

Adhesive bonding not only seals the joints, but also prevents crevice and galvanic corrosion between two dissimilar materials. Almost any pair of dissimilar materials such as metals, polymers or ceramics can be joined with this method. Adhesive bonding is the only viable method to achieve structures involving the joining of thin-walled elements, among which an element has substantial dissimilar thickness. Adhesive bonding offers light-weighted structures with respect to other assembly technologies and developments, particularly in aviation industries. In addition, stress concentration becomes less significant without the requirement of bolt holes, thus avoiding structure weakening [20]. The adhesives as the main elements in adhesive bonding should have good wettability with respect to joining components, such as CFRPs and aluminium alloys.

1.5 Improve adhesive bonding with surface modification

Prior to a bonding process, adherents are required to be thoroughly cleaned, which means that any contamination removal should be made by degreasing either via mechanical polishing or by using wipe cloths in order for the surfaces to be bonded. Hence the preparation depends primarily on adherents and adhesives to be used in the joining process. Emery papers of different grades and solvents like acetone can be used for this purpose. Usually etching or light abrasion is followed by the solvent wipe to get rid of grease and other loose dirt. Etching can be carried out in a chemical manner by using hydrochloric acid and water (e.g. 20–80%). Despite such a quick process, it discolours metal surfaces owing to the oxidation effect. A universal etchant, used for aluminium alloys, involves chemical etching before microstructural contrasting in polarized light. Detergents must be avoided for both components in that they can further aggravate contamination [21].

In case of aluminium alloys, surface films in the formation of aluminium oxide (Al2O3) are unavoidable upon exposure to air or water, resulting from very low wetting capability. such tenacious films are hard to remove with the requirement of extensive chemical treatment [22]. Therefore, the surface should be chemically modified in order to prevent such film formation in first place. This can be done either by adding coupling reagents or by anodizing [21]. Coupling reagents form such strong and irreversible covalent bonds between surface oxides and hydroxides, which are in turn linked with adhesive during the curing process. On the other hand, anodizing results in the formation of rough and water-resistant oxide films at micro scale level by using sulphuric, phosphoric or chromic acid. Sulphuric acid treatment is used in lightly stressed joints to obtain the best results for the application of elastic adhesives. Anodizing with chromic and phosphoric acid is performed for highly stressed joints, which are meant to be used in the corrosive environment. This process actually forms regular micro pores in oxide layers towards underneath metal surfaces. During the curing process, adhesives fill up those micro pores and eventually reach the metal surfaces. The treatment with phosphoric acid gives best results when used with low viscosity prime [22]. If proper steps are followed to clean the surfaces using such strong oxidizing agents, the results of this can lead to excellent surface finish without deteriorating their properties. Afterwards the application of primer prepares the surface for adhesion with stronger and more uniform bonding [23].

In addition to chemical treatment, acetylene and nitrogen plasma can also be used to modify aluminium panel towards adhesive bonding [24]. This plasma treatment modifies the surface characteristics of structures, as evidenced by the change in contact angle between aluminium and water from 82° to 135°. The contact angle was minimum in a gas mixture of acetylene/ nitrogen with a volume ratio of 3:7 for the exposure time of 90 s as opposed to 5:5 for 30 s. Primer is recommended to be used for the components in the corrosive environment or where pre-treatments do not offer any obvious benefits. Most recommended treatments for aluminium alloys consist of a pre-treatment procedure that includes degreasing of materials, rinsing, acid/base etching, which are followed by a final rinse. The most commonly used etching solutions are sulphuric/ chromic acid or sodium dichromate. Adhesives should be applied immediately to avoid any further contamination of freshly prepared metal surfaces [25]. Surface preparation and treatments at optimal conditions are prerequisite towards superior adhesive bonding. There are a number of options available towards that and optimum parameters should be considered based on availability and materials in question.

A number of theories are available in literatures to describe adhesive bonding mechanism, namely adsorption and diffusion theories, and mechanical mechanism. These different theories and their contributions to the understanding of adhesive bonding mechanism are discussed briefly in subsequent sections:

1) Adsorption: According to adsorption theory, adhesive provided an intimate contact between adherents due to the inter-atomic and inter-molecular forces at interface. Lewis acid-base and van der Waals interactions generate those interfacial forces. The amount of these forces depends on vital thermodynamic parameters like surface free energies of both adhesive and adherent. The first step towards bond formation is liquid-solid interaction and therefore good wetting of the surfaces dictate overall adhesion quality. According to electronic theory of adhesion, mechanism of an electron transfer stimulate substrate and adhesive which have dissimilar electronic band configurations and can balance Fermi levels. This induces double electrical layer generation at interface and thus electrostatic forces are generated which back adhesive strength considerably [21, 22, 26].

2) Diffusion theory: According to this theory, adhesion strength of polymers to polymers, or polymers to others is associated with the inter-diffusion of molecules through interface for the interphase generation. Thus the presence of macromolecular chains or parts of chains that are appropriately mobile and mutually soluble in the interphases, enables the adhesion process for self-healing and welding. Joint strength for interdiffusion phenomena depends on diverse aspects,

namely contact time, temperature, nature and molecular weight of polymers and so on. Chemical interactions in substrate-adhesive interfaces significantly contribute to adhesion between joining parts, which are usually assumed as main bonds as compared to physical interactions. For instance, van der Waals interactions are wellknown as secondary force interactions. The molecules of adhesion additives, generally knows as coupling agent (based on silane molecules), promotes interfacial chemical bonds and increase the strength of joint between substrates and adhesives by forming a chemical linkage at borders . Those are usually active in structures including glass or silica substrates and further specifically in CFRPs. In addition to the improved joint strength, coupling agents also resist the moisture on interfaces [27].

3) Mechanical keying or interlocking: Mechanical keying allows adhesives to wet cavities, pores and asperities of adherent surfaces and thus contributes to adhesive strength significantly after curing. Nonetheless, the chance to from decent adhesion among smooth surfaces indicates that theory of mechanical keying is not universal. The effects of mechanical interlocking and thermodynamic interfacial interactions are multiplying factors for assessing joint strength and the intensification of adhesion by mechanical keying is attributed to the increase in interfacial areas because of rougher surfaces. Moreover, wetting conditions enhance the adhesive penetration in pores and cavities. For example, high peel strength of polyethylene on metallic substrates can be achieved when rougher and fibrous oxide surfaces are formed, and the further improvement can be obtained by utilizing plasma surface treatment. In that case, the prolonged plasma treatment creates a rougher configuration on polyethylene surfaces, filled by epoxy resin later with dints of good surface wetting [28, 29].

In reality, all above-mentioned mechanisms contribute to the strength of adhesive joints. Once adhesives and substrates are in contact, attraction forces start to act between them with adequate wetting, these forces are usually sufficient to afford high strength bonding. Main bonding is essential to achieve durable bonding in an aggressive atmosphere. Mechanical interlocking among rough surfaces and adhesives also require good wetting, otherwise surface roughening is likely to cause inferior bond strength. Superior adhesion is related to increased plastic energy release at the time of fracture in main adhesive parts. Electrostatic concept heads for electrical phenomena such as sparking, which may occur at the time of adhesive bonding break. The electrostatic charge transmission between substrates and adhesives is analogous to a parallel plate condenser. The energy related to this process is usually too small compared to that of adhesion fracture. A diffusion concept has attracted increasing interests in the provision of a model for polymer-to-polymer adhesion, which explains the dependence of adhesion on time and molecular weight for polymers with different compatibilities [21-30].

2 Summary

In our future work we would joining aluminium foam to aluminium foam using adhesives and different surface preparations. The foams should be closed cells foams. The adhesive can contain be one, two or more components.

Our hypothesis is that, the different surface treatments, for example: grinding, polishing, acid etching, plasma treatment, laser treatment could change the wettability and the joint quality between the foams. We would investigate the surface of the foams after the preparations, the connection quality between the modified surfaces and the adhesives. The effect of the surface modification can be investigated on the micro and macro topology. The quality of the joint can be measured with tensile strength.

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