Aluminium foams for energy absorbing structures under axial loading

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Abstract

In the Audi A8 car the deformation energy for speeds up to 10 km/h is absorbed by the reversible deformation of an impact damper. For speeds between 10 and 20 km/h the sequential buckling of easily replaceable circular aluminium tubes works as energy absorbing mechanism in order to prevent damage to the frame body due to low speed impact. Besides increasing the wall thickness, utilising foam filled structures is one possibility for improving the energy absorbing properties of these tubes. When doing this two mechanisms have to be distinguished. One mechanism is a parallel action of foam body and tube, which means that the foam body does not influence the buckling process. The other mechanism involves an interaction between the foam and tube which can be attained by locating the foam as close to the tube wall as possible. Although the efficiency of structural foams based on aluminium or epoxy (EP) is significantly higher than that of an empty tube, the mass-related energy absorption of aluminium foam components is lower. Nevertheless, due to the interaction between the foam and the buckling process, the effectiveness of the structure can be improved. Besides the degree of filling the tube with foam, the applied joining technique affects the energy absorbing properties, too. Whereas gluing does not show much effect on the deformation process, laser beam welding leads to a lower peak load necessary for initiating the buckling process due to the reduced strength of the tube material in the area of the welding seam. However, comparative experiments show that Al-tubes lined with a 2 mm-thick EP-foam layer show better mass specific properties than those filled with an 8 mm-thick Al-foam layer.

1 Introduction

The front structures of modern cars possess a graded deformation behaviour: with increasing impact speed different energy absorbing systems act to absorb the kinetic energy (Fig. 1). In order to protect the body frame from damage and to reduce repair costs, various systems for low speed impacts are applied. In the case of the AUDI A8, for speeds of up to 10 km/h this is done by the reversible deformation of an impact damper. The energy for speeds between 10 km/h and 20 km/h is absorbed by the sequential buckling of circular aluminium tubes [1], which can be simply replaced after a crash. Increasing the energy absorption potential of these tubes is possible in two ways:

- increasing the wall thickness of the tube
- integrating a foam body into the tube

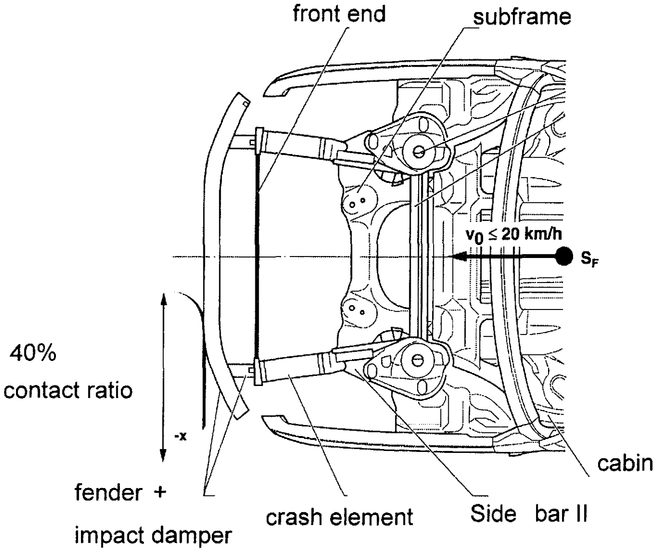

Fig. 1: Schematic drawing of the front structure of a car

2 Experimental Set-up

2.1 Crash Experiments

The AUDI A8 crash elements used in the experiments were seamless hollow extruded circular aluminium tubes. They had a length of 328 mm, a diameter of 100 mm and a wall thickness of 2 mm. The powder metallurgically produced foam bodies of an aluminium wrought alloy can be seen in Fig. 2.

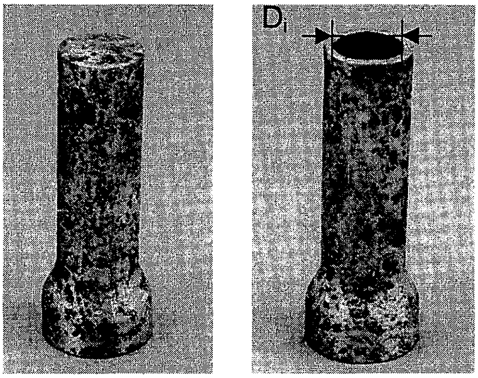

Fig. 2: Foam bodies for light interaction between foam body and tube

For the crash components, the porous structure was fixed in the tube with the use of a conventional adhesive used in the automotive industry. The experiments were carried out with the help of a crash sled. The mass of this sled varied between 130 kg (empty tube) and 173 kg (D_i = 0 mm) and the impact speed was between 13 and 14 m/s.

2.2 Laser beam welded structures

Laser beam welding has already been proved as a feasible process for joining aluminium foams and aluminium semi-finished products [2]. The samples were welded with a 2 kW Nd:YAG-laser. This laser can be used in cw- or pulsed mode. For the given task, a mixture of the two modes was chosen, since when welding aluminium alloys with Nd:YAG-lasers, the keyhole effect can be realised more easily in the pulsed mode. Seamless hollow aluminium tubes were extruded out of AA6009 with a length of 100 mm, diameter of 50 mm and wall thickness of 1.5 mm. Foam bodies were machined out of AA6082 foam sheets which were produced by the cast method and contained particles of Al_2O_3 in order to increase the viscosity of the melt. The welding speed was 2.1 mm/min.Various filling grades of the tube were obtained by varying the outer diameter D_0 of the foam cylinders (see Fig. 4). Testing of the tubes was done with a Zwick Universal Testing Machine Z100 at a deformation speed of 10 mm/min.

2.3 Characterising the energy absorbing behaviour

For characterising the properties of energy absorbing structures, key parameters have to be defined:

Efficiency [3]:

$$\eta = \frac{\int_0^{s_{\max}} F(s)ds}{F_{\max} \cdot s_{\max}} \qquad (1)$$

Load Uniformity (LU) Factor [4]:

$$LU = \frac{F_{\max}}{F_{mean}} \qquad (2)$$

3 Results and Discussion

3.1 Increasing the wall thickness of the tube

The energy absorbing properties of Al-tubes are almost not influenced by increasing the wall thickness, as the peak load necessary for initiating the buckling process and the mean load during the deformation rise about the same percentage. Though increasing the wall thickness leads to the desired increase of the absorbed energy, it has a negative influence on the compressive load-strain curve during the deformation (Fig. 3). The increase of the peak load corresponds with higher decelerations for the vehicle passengers. Additionally, the load variations during the buckling process become large. This is not desirable as well, as the loading process of an efficient structure should be as constant as possible.

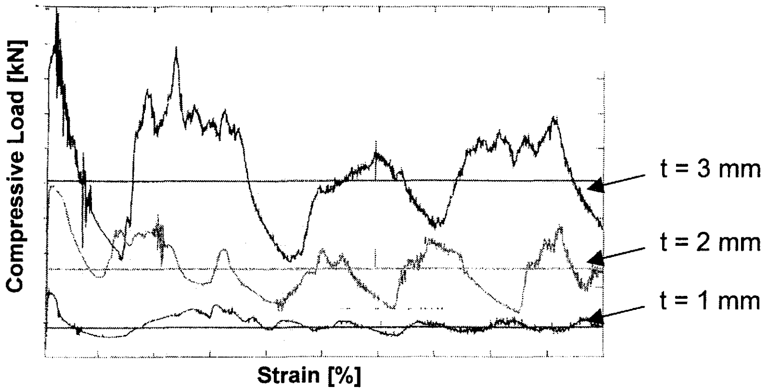

Fig. 3: Influence of the wall thickness of the energy absorbing behaviour

3.2 Integrating a foam body into the tube

In integrating an aluminium foam body into the structure, two basic mechanisms have to be distinguished:

- no interaction between foam body and tube, i.e. the buckling process is not influenced by the foam body and the resulting compressive load – strain curve is a summation of the individual loading processes
- interaction between foam body and tube, i.e. the buckling process is influenced by the foam, as the foam is compressed axial (by the load) and lateral (by the buckles)

In both cases the peak load necessary for initiating the buckling process remains constant, i.e. only the mean load increases (Fig. 4).

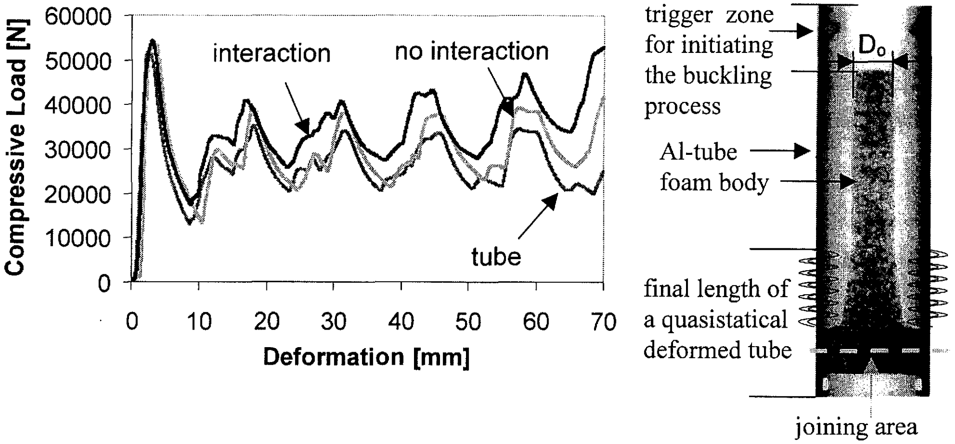

Fig. 4: Compressive load – deformation curves of compound structures with and without interaction and a corresponding radiograph of a compound structure

Figure 4 shows a X-ray radiograph of a partially filled crash element. If no interaction between tube and foam body is wanted, the outer diameter D_o of the foam body has to be small enough in order to prevent an interaction with the tube, whereas the minimum diameter is limited by the collapsing of the porous structure, i.e. an uncontrolled energy absorbing process of the foam body.

Fig. 5: Influence of D_i on the compressive load – deformation curveWhen utilising a foam body which interacts with the buckling process the compressive load – strain curve is influenced by the degree of filling of the tube, whose variation is possible by changing the inner diameter of the foam body (Fig. 5). With decreasing inner diameter D_i (compare Fig. 2) the slope of the curve increases, i.e. the more foam material is used, the more rapid is the increase in the compressive load after the initiation of the buckling process. Usually this load at the onset of buckling should not be exceeded for longer than 3 ms in order to prevent injury to the vehicle passengers. Structures, whose relationship between maximum usable deformation length and length of the structure is small, have a low value of geometric efficiency [5], as a large part of the structure remains unused.

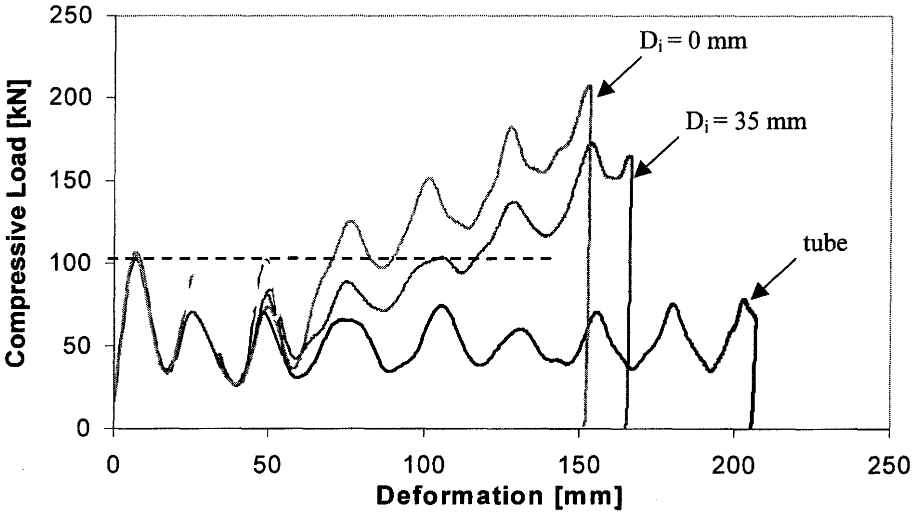

Fig. 5: Influence of D_i on the compressive load – deformation curve

3.3 Laser beam welded structures

Laser beam welding of aluminium foams to aluminium semi-finished products leads to a joint, which is based on a material- and shape-related connection mechanism [2]. Due to the deeper penetration of the laser beam, a large amount of the foam structure neighbouring the tube-foam interface is included in the joining zone. The locally concentrated heat input during the welding process reduces the strength in the heat affected zone; i.e. the welding seam triggers the buckling process at a load significantly lower than that for unwelded structures (Fig. 6). The difference in the amount of the absorbed energy between welded and unwelded structures is very small, as only the first narrow peak of the deformation curve is affected, whereas the further loading process is not influenced by the joining process. Consequently laser beam welding has a positive effect on the energy absorbing structure as the critical peak load at the beginning of the deformation is reduced and the loading process gets more homogenous.

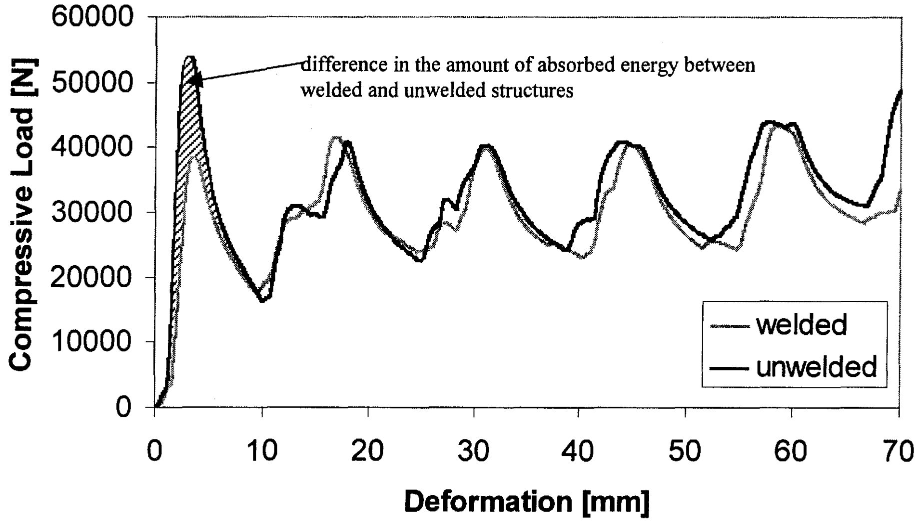

Fig. 6: Influence of laser beam welding on the compressive load – deformation curve

3.4 Energy absorbing properties of the investigated structures

Increasing the interaction between the tube and the foam material is possible by lining the inner tube wall with foam. For comparative reasons this experiment was carried out with an 8 mm thick aluminium foam layer and a 2 mm thick layer of epoxy foam. Due to the direct contact between the porous structure and the massive material, the buckling process is affected more strongly which leads to a more homogeneous loading process during the deformation. Additionally there is no steep increase in the load after the formation of the first few buckles, as it is the case when light interaction is applied (see Fig. 5). This means that the densification of the foam does not influence the energy absorbing behaviour of the structure negatively. With respect to the key parameters used to describe the energy absorption behaviour, two different results can be seen when lining a crash element with EP-foam or Al-foam. Whereas the LU-factor decreases in both cases due to an increase in the mean force during the deformation, the influence on the specific efficiency depends on the type of foam. The EP-foam lining leads to a slight increase of the specific efficiency compared to an empty tube, whereas the value of a compound structure with an 8 mm thick Al-foam layer decreases. In consequence, the application of Al-foam body components in Al crash elements is not adviseable as long as the producible cross sections and densities of foam body components remain much higher than that of EP-foams.

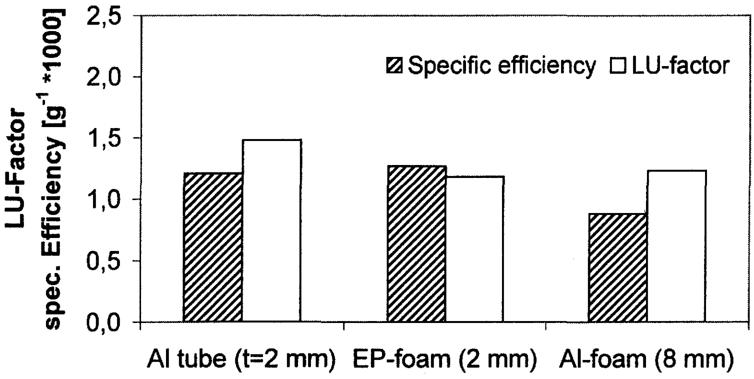

Fig. 7: Results of component experiments

The LU-factor of unwelded structures decreases with the filling level of the structure (decreasing the outer diameter D_0 of the foam body (Fig. 4)), due to the increasing mean force during deformation. In laser beam welded (lbw) structures, the significant decrease of the peak load which is necessary for initiating the buckling process, leads to a further reduction of the LU-factor. Additionally the more homogeneous loading process of laser beam welded structures results in an increase in the specific efficiency compared to identical unwelded structures. In summary laser beam welding not only serves as a simple joining technique, it additionally improves the properties of the given structures.

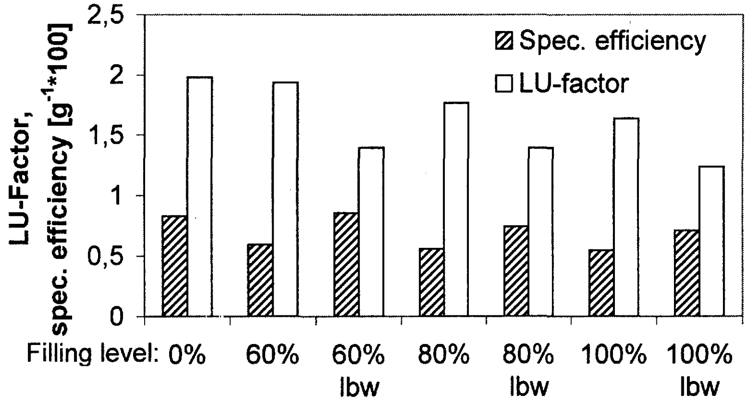

Fig.8: Influence of laser beam welding (lbw) and the filling level on the energy absorption behaviour

4 Conclusions

Although the energy absorbing potential of aluminium tubes used as energy absorbing structures for low speed impacts can be improved by increasing the wall thickness, it is more advisable to utilise foam-filled structures, as the peak load necessary for inititating the buckling process is not influenced by the filling. Additionally the load variations during buckling increase with the wall thickness, whereas they can be minimised by an adequate integration of the foam body. Two basic mechanisms have to be distinguished when integrating the foam body. The first mechanism assumes no interaction between the porous structure and the tube, i.e. foam and tube act independently and the resulting compressive load – strain curve is a summation of the individual deformations. The results of compound structures with an interaction between the tube and the foam show that partially-filled structures show better mass specific properties than completely filled ones. Comparative experiments with Al-tube lined with EP-foam and Al-foam yield better mass specific values for the EP-foam, as the minium producible densities and wall thicknesses of aluminium foams are still too high for energy absorbing applications in aluminium crash elements. The joining technique influences the properties also. Whereas gluing does not show much influence on the deformation behaviour, laser beam welded samples start deforming at significantly lower peak loads which results in better values of the LU-factor and the specific efficiency.

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