Passive Energy Absorption Using Structured PP Foam

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When launching international models, carmakers have to address the standards specified by the whole range of markets. Standards applying to the US market are becoming increasingly important especially for European OEMs. The new Jaguar X-Type was able to meet the stringent criteria of the US Federal Motor Vehicle Safety Standard (FMVSS) 201U for passive energy absorption in the passenger cabin following exhaustive series of tests, thanks to a novel polypropylene foam material. The honeycomb structure of this new material from Dow Automotive offers maximum energy absorption with a minimum space requirement.

1 Introduction

There is a recognisable global trend within the automotive industry that is actively seeking to improve passenger safety in the event of an accident. This awareness finds expression in numerous safety measures which are largely fitted as standard – often invisibly – and which are frequently the subject of consumer advertising. Results of governmental and institutional crash ratings are being leveraged as marketing tools. In addition to active restraint systems such as seat belts and airbags, today’s vehicles are therefore fitted with various passive energy absorbers which yield in a controlled fashion in the event of impact and help to avoid injuries, especially to the head. For this reason, automotive R&D engineers are constantly searching for new, high-performance materials in order to meet the increasingly stringent legal requirements and demands for safety.

The headliner area is one such challenge. On the one hand, the FMVSS 201U [1], which is applicable in the US, specifies very precise admissible loads for the head, while, on the other hand, the available space is highly restricted because of styling considerations. A new type of polypropylene-based foam has been launched under the trademark “Strandfoam EA”, which has excellent properties, particularly with regard to energy absorption, thanks to its unique structure. Its ability to absorb a maximum of energy while requiring only minimal packaging space makes this material ideal for use behind the headliner. It is also suited to pillar trims, protective padding, steering column trims or door linings, Figure 1. Its ability to meet practical requirements has already been demonstrated in the US, where this material helped DaimlerChrysler to comply with FMVSS 201U in the Dodge Neon and Chrysler Intrepid. Now, for the first time, a model incorporating this innovative material is entering the European market in the new X-Type from Jaguar.

2 Material Properties

2.1 Comparison of Foam Materials

In order to understand the new foam’s special properties, it is necessary to have a closer look at the structure of the material and its manufacturing process. Most of the foams used by automotive engineers for energy absorption are based on polyurethane (PU) or expanded polypropylene (EPP). These are turned into a homogenous, porous structure with uniformly distributed cells using chemical and physical blowing agents. The material properties are consequently largely isotropic.

The new foam material, by contrast, is composed of parallel foam strands which demonstrate excellent properties in the preferred orientation – similar to a composite material. These foam strands are produced in a patented process in which a polymer melt mixed with physical blowing agents is extruded through a multi-orifice die [2, 3]. This results in parallel strands which expand to a diameter of approx. 5 mm and fuse together into a characteristic honeycomb structure, Figure 2.

You will find the figures mentioned in this article in the German issue of ATZ 5/2001 beginning on page 406.
Each foam strand is enclosed by a thin “skin”. In fact, in these strand interfaces, the foam has a significantly smaller cell size and a higher density. The presence of this skin is extremely important in the properties discussed below. The resulting foam block is cut into panels of the desired thickness transversely to the strand orientation, and these panels are further processed into systems ready for installation into vehicles.

### 2.2 Load Properties

Strand foam has significantly different properties under load from conventional materials. Its performance under static loading will be examined first to provide a better understanding of these properties. Conventional foams have extremely uniform properties under a static compressive load. After a brief elastic phase with moderate rigidity, the foam cells exhibit plastic deformation. The force increases continuously as the cells are compressed. Finally, the foam is compressed into a densified medium, and the force quickly rises to very high levels. A material’s energy absorption is characterised by the area under the load/deformation curve. A popular means of rating the energy-absorbing capability of foams is the “efficiency factor”. This figure expresses the ratio of the actually absorbed energy to the theoretically ideal energy absorption, and enables a qualitative comparison of two materials to be made.

The most important variable for adapting to a given load is the foam density. Any change in the density deforms the load/deformation curve in a vertical direction, re-scaling it, as it were, in the load direction, while the curve remains essentially unchanged. In other words, the utilisation factor does not change. The situation is similar if the foam type is varied. EPP or PU differ in their characteristic values, but the shape of their curve is largely unchanged. The narrow, initial elastic range, the broad plastic range with a continuously rising curve and finally complete compression with very high reaction forces can always be identified. The utilisation factor ranges between 40% and 75%. It is therefore not possible to make optimum use of the available space.

Thus, while conventional foams always exhibit a continuously rising load/deformation curve, strand foam (for the same density under a compressive load in the strand direction) is initially considerably more rigid, and - upon reaching a critical load - will continue to deform under an almost constant force, Figure 2. This is much closer to ideal absorption properties, enabling utilisation factors of over 90% to be achieved.

#### 2.3 Dynamic Properties

When considering the dynamic implications, it is important not only to absorb the energy within a specified distance but also to avoid certain critical decelerations for the head. The efficiency factor is not a suitable measure of this and cannot make any meaningful prediction of load peaks, maximum acceleration, possible injury risk or even the probability of survival.

It is precisely these aspects that are rated by the US-specified “Head Injury Criterion” and expressed as a coefficient, the HIC [3]. This is calculated by integrating the measured acceleration of a head impact event within a maximum time interval of 36 milliseconds, with exponential weighting being used to penalise high, sustained decelerations which are damaging to the human brain:

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\text{HIC} = \left[ \left( \frac{1}{(t_2 - t_1)^{25}} \right) \int_{t_1}^{t_2} (t - t_1) \right]_{\text{max}}
$$

The HIC is therefore a measure of the damage to the head (or the performance capability of an energy absorber), whose critical value is set at 1000 by European and US legislation. Most carmakers actually specify a figure of no more than 800.

The required properties of an effective head impact cushion can be derived from the following definition: The head must be decelerated at a constantly high, though not yet critical rate for the entire duration of the impact event. This requires a high initial rigidity (to achieve a high deceleration level quickly), after which this level must be maintained without further rises. Such a force/deformation curve, as right-angled as possible, would be expressed in efficiency factors of almost 100% and make the best possible use of the available packaging space.

Designing a head-impact protection system using conventional foam is subject to numerous constraints. If packaging space is small, varying the foam density or type offers only limited improvement options. An (excessively) soft foam only enables short decelerations to be achieved, absorbs little energy and is soon compressed into a block. The head is then abruptly decelerated, which is expressed in high HIC figures. Although an (excessively) hard foam begins to decelerate the head rapidly, the already high decelerations rise further with increasing compression, with the result that, here too, the HIC figures are unacceptable. In critical cases, the only means of achieving permissible HIC figures is then to increase the thickness of the component. Only materials with a significantly better efficiency factor - such as the new strand foam - offer a solution.

The advantageous compression properties of the strand foam result from its structure, i.e. the presence of varying foam densities within a strand and its surrounding skin. The reinforcing effect of the skin around each individual strand gives the material an additional initial rigidity, with the foam, the skin and the strands supporting each other to prevent buckling. The absolute level of this critical buckling load can be set via the foam density. Once this has been exceeded, the strands are compressed in a controlled fashion, the skin begins to fold like a crushed drink can and the strands de-laminate, Figure 5. This collapse absorbs a considerable amount of energy and occurs with an almost ideal load/deformation curve without load peaks.

The deformation behaviour of the honeycomb structure has been achieved by specifically matching the skin thickness to the strand diameter. The densely closed-cell foam structure is also an important factor in the mechanical properties cited. An HMS (high melt strength) polypropylene is used to prevent the foam bubbles from bursting during the blowing process. If a standard polypropylene were used, this would merely yield an open-pored foam which would at best be suitable for sound insulation.

Compared with the other materials used for energy absorption, which take up impact energy solely by compression, strand foam uses the combination of three energy-absorbing mechanisms – compression, buckling and delamination – to deliver its excellent performance.

#### 3 Benchmarking

The dynamic properties of the strand foam were compared with those of other materials in a close-to-reality, generic head impact test. A sheet-steel section represented the vehicle body whose rigidity could be adapted to the limited yielding properties of a “genuine” pillar structure by varying the sheet thickness. The absorbent material under test was then attached to this, after which a free motion head form (to FMVSS 201U) was fired at it at a speed of 6.7 m/s. Ac-