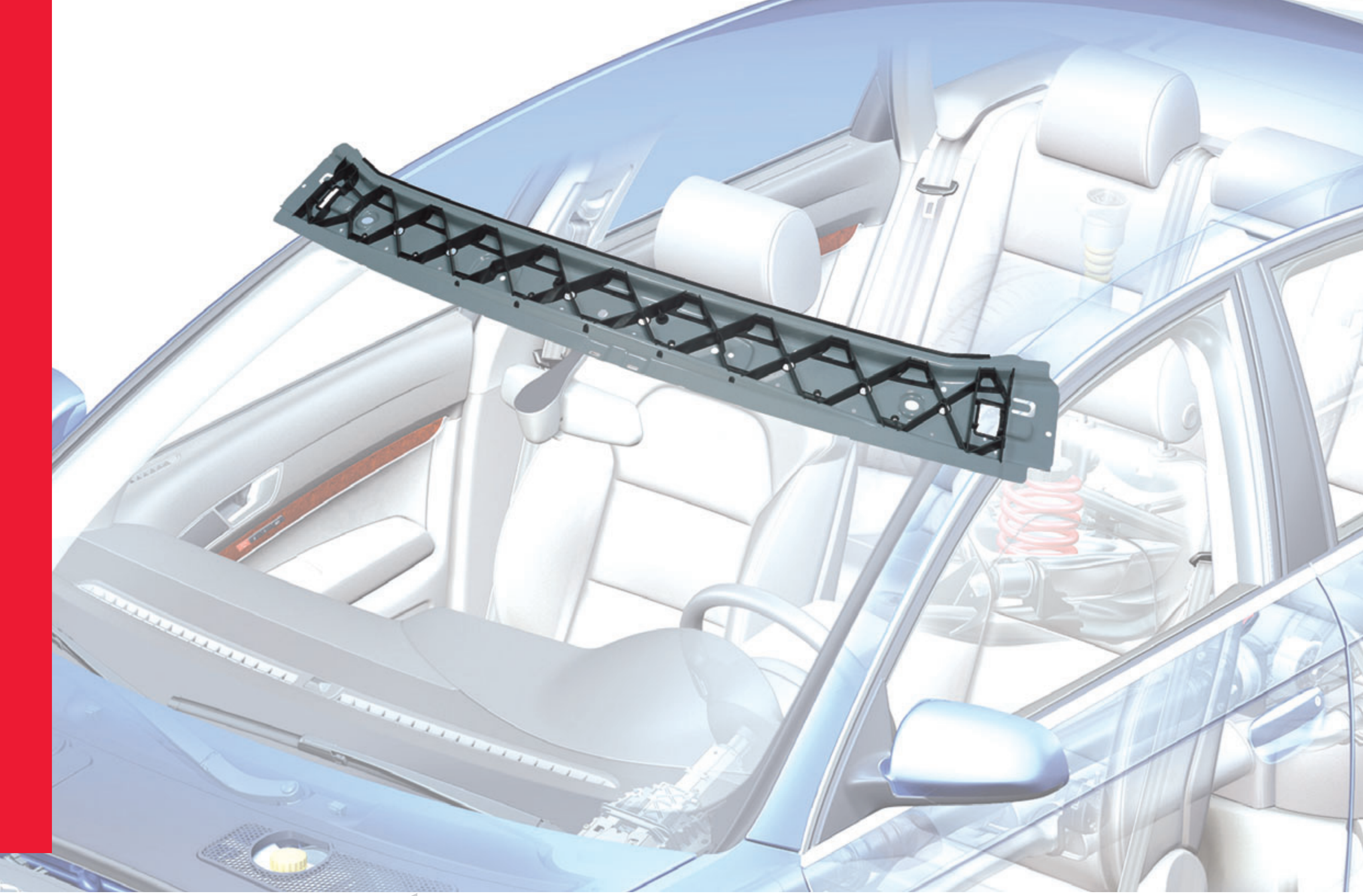

Reprint from VDI-Report No. 4261 (2004), pages 25 - 45

Roof-frame design using hybrid technology

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General information about hybrid technology

Definition of hybrid technology

The term 'hybrid technology' is being used increasingly these days for certain technical applications. One application of hybrid technology, deriving from a patent of Bayer AG, Leverkusen, takes the form of a composite of the two materials of plastic and metal and it is with this that the present contribution will be concerned.
The word 'hybrid' is of Latin origin and is defined by the Oxford English Dictionary as "the offspring of two animals or plants of different species, or (less strictly) varieties". Accordingly, the term 'hybrid technology' implicitly claims that different technologies are used alongside each other and must work with each other.

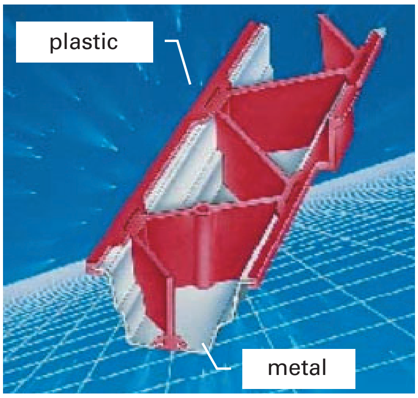

Fig.1: Hybrid structure: plastic/ metal composite [2]

As has already been stated, in this paper we take hybrid technology to relate to a composite of the two materials, plastic and metal, which can be produced using the injection moulding method (cf. Fig. 1). The resulting hybrid structure combines the advantages of the two materials together with the corresponding processing and machining techniques. [1]
The hybrid construction basically consists of a thin-walled sheet steel structure forming a composite with suitably designed plastic sections (see also Fig. 1) which give the metal the mechanical properties it requires.

Manufacture of hybrid components

Not only the specific properties of the materials used but also the two economically efficient processing methods of metal deepdrawing and injection moulding supplement each other with the result that reliable, reproducible and close manufacturing tolerances are possible. This means that complex, ready-to-assemble components can be manufactured in just a few operations.
Following insertion and fastening of the thin-walled, deep-drawn, stamped and in itself still not very robust sheet metal structure, the plastic structure is moulded on by standard injection moulding using a suitable material (cf. Fig. 2) [2].

Here, during the filling procedure, the plastic melt pushes through the openings, seams and past the circumferential edges of the sheet metal and forms a rivet head or a clip between the cavity wall of the mould and the inserted metal part.

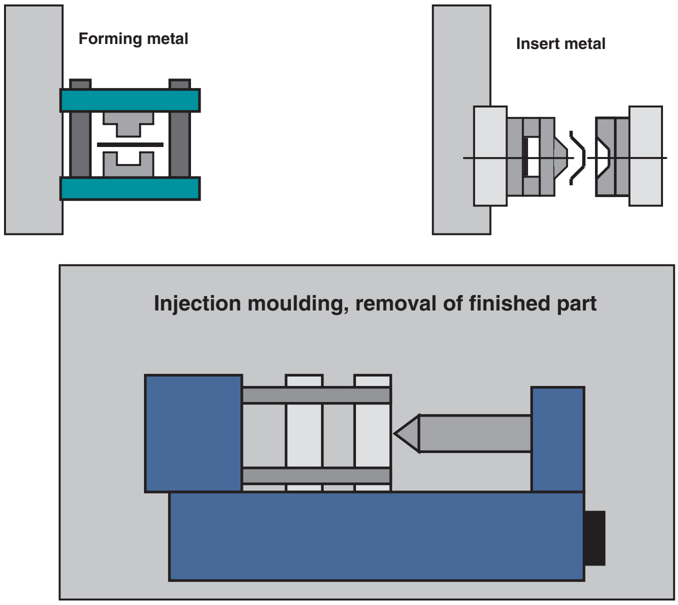

Fig. 2: Principle behind manufacturing hybrid components [1]

Potential savings with hybrid technology

In the automotive industry, as a way of opposing the weight spiral, even load-bearing metal structures, among other things, are frequently made from thin-walled sheet metal profiles. Constructions of this kind do, however, have their weak points in the area of force input points since loads cannot be introduced over a large area into the component.
By moulding on rib-shaped reinforcements and stiffening elements made of plastic, it is possible to strengthen thin-walled steel structures very effectively with little additional weight.
In addition to the reinforcing ribs, hybrid technology, in a similar way to the insert or 'outsert' method, offers the possibility, thanks to injection moulding, of integrating in a single process step all kinds of additional features, such as fastening elements, bearing points, latching hooks, screwed connections, cable clips and so on. This makes it possible to make savings in time- and cost-intensive secondary finishing and assembly processes.
On the basis of the aspects we have briefly described, we may list the advantages which hybrid technology can offer [1]:

- Weight reduction
- Cost reduction
- Rational manufacture
- High functional integration
- High reproducible precision
- High rigidity
- High energy absorption
- High load-bearing capacity
- High degree of ruggedness

Preliminary technical investigations

Use of hybrid components in the construction of vehicles does however mean that, as regards requirements relating to odour, emissions, fogging and so on, they must satisfy

the same requirements within the process chain and as regards corrosion protection as must comparable all-metal components.
In order to be able to determine the load-bearing capacity of a hybrid profile in comparison with purely metal designs, Bayer and the University of Erlangen built an injection mould for ribbed, three-dimensional hybrid structures (U-shaped hybrid beams). Extensive preliminary technical investigations were carried out on these test supports.

Fogging, emissions and odour

Fogging, emissions and odour are requirements applicable to materials or components in the vehicle interior and luggage compartment as well as to parts which come into contact with the air flowing into the vehicle interior. At Audi the standard VW 501 80 applies. According to this, with new designs the only materials which may be used (in this case the plastic of the hybrid component) are those which remain below the limit values specified in the standard [3].
The behaviour as regards fogging, emissions and odour which must satisfy the values defined in the standards and inspection specifications before any use is permitted in the vehicle interior, was examined on the basis of the plastics Durethan BKV 130 H2.0 and Durethan BKV 30 H2.0.

As regards the aspects of emissions and odour, approval could not be given for Durethan BKV 130. According to the results, the responsibility for the poorer evaluation of the odour in the case of the Durethan BKV 130 lies with the rubber components.

The consequence of the test is that the selection of materials for hybrid bodyshell parts is restricted to Durethan BKV 30 which was then used in all subsequent tests.

Process-determined requirements

In what follows, from the stations in the process chain of vehicle production, we shall ascertain what are the process-determined requirements applicable to hybrid components.

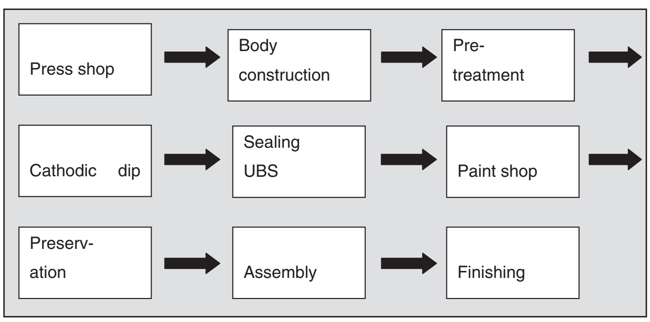

Fig. 3: Process chain for vehicle production [1]

Press shop

In the press shop the individual parts of the body (for example, side panel frame, doors, wings or longitudinal members) are shaped. To do so, the sheet metal, in the form of rolls or sheets, is cut and then pressed in the shaping presses into the automotive components required.

Before the actual pressing process itself, the sheets are partially lubricated with drawing compound. This ensures that there is the lowest possible friction between the shaping die and the sheet metal, and also has another advantage: the sheet metal can be pulled more easily over the radii in the mould. This production process results in the first requirement applicable to the metal-plastic composite. The plastic used must be resistant to the drawing compound since for reasons of cost the compound should not be washed off before the sheet metal is inserted into the injection mould (cleaning of the body and thus of the hybrid component takes place in the pretreatment station).

Body construction

Here the bodyshell is put together from individual parts or prefabricated assemblies. In this step, different joining methods are used: welding, gluing or lock-seaming. A further requirement applicable to the hybrid component – here, the metal – is therefore that it is suitable for joining (particularly welding).

Pre-treatment

The process of pre-treatment is required to ensure that the body is clean and greasefree before painting since only in this way can perfect adhesion of the paint be guaranteed. Pre-treatment consists of the two processes of cleaning and phosphatizing. During the cleaning step, the bodyshell is passed several times through a bath containing a cleaning agent at a temperature of 57 °C and each time rinsed with deionized water: this degreases the bodyshell. In the phosphatizing step, a thin layer of phosphate (cation phosphatizing, zinc, nickel, manganese) is applied at 55 °C to the metal surfaces. This permits adhesion between inorganic metal and organic paint (cathodic dip painting).
This step in the process chain makes the following equirements on the plastic of the hybrid component: the plastic on the one hand must retain its properties even after the pretreatment stages and on the other hand should not be the source of any contaminants which would affect the baths and thus the surface of the body (the plastic must also be able to cope with the baths).

Cathodic dip painting

Cathodic dip painting (also known as cataphoresis or priming) is a variety of electrodeposition painting and provides not only corrosion protection for the steel parts of the body but also an adhesion substrate for subsequent paint application (priming). Here the body is immersed for coating in a dipping tank containing water-soluble paint. When the body is immersed in the isolated tank, special electrodes create a flow of current through the conductive paint to the bodyshell. Following chemical reaction in the binder (coagulation) a continuous film of paint appears on the steel surfaces (since plastic is not electrically conductive, no electrophoretically deposited paint adheres to hybrid components). The paint is then stoved in the drying oven for 40 minutes at about 200 °C (curing is initiated). What this means for the hybrid component is that the plastic must tolerate cathodic dip painting: in other words, no components of the plastic should be released (see above).

Furthermore, it must retain its range of properties even after the cathodic dip painting tank and also the exposure to higher temperatures.

Paint shop

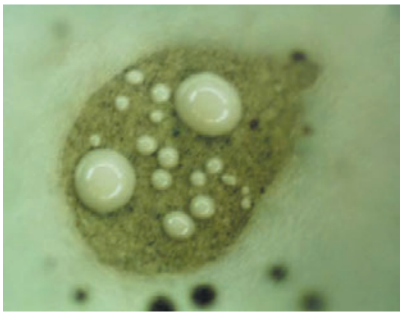

Fig: 4: Wetting defect (a crater under the microscope) [1]

The plastic should not be the source of any undesirable potential for problems (such as, for example, craters or wetting defects). These arise when, due to their surface tension, substances prevent the paint from wetting the surface adequately. Responsible for paint flaws of this kind, such as may be seen in Fig. 4, are primarily greases, oils, separating agents and also silicones which under certain circumstances can emerge from the plastic and cause contamination.
What this means for the hybrid component is that the plastic must be paint-tolerant: in other words, no components of the plastic should be released (see above).

Summary of results

In collaboration with Bayer – material manufacturer, patent-holder and source of knowledge in the field of hybrid technology – we were able to demonstrate that the material Durethan BKV 30 H2.0 was resistant to the media used (no contamination of the baths) and that the properties of the plastic were retained after passing through the process.

Corrosion behaviour

One important precondition for the use of hybrid technology in body construction is that that Audi's corrosion requirements are satisfied. Here the car is subdivided into various 'corrosion sections' which include dry sections (exposed to little corrosion), moist sections (subject to a minor amount of corrosion) and wet sections (subject to a higher degree of corrosion). For each of these sections, different requirements apply with regard to corrosion properties, and the result is that a 12-year guarantee against corrosive penetration of the body can be given.
By *passive corrosion protection* is meant the application of a layer of a protective material which hinders attack by corrosive media. Here the coating thicknesses may range from 10-3 to several millimetres. At Audi the entire body (in other words, all metal components) is protected against corrosion by a primer coat applied by cathodic dip painting (cataphoretic paint) [1].

Corrosion of hybrid components

As part of preliminary investigations, it was ascertained whether a component with a hybrid structure would satisfy the same requirements as comparable metal components. As far as corrosion is concerned, it was important to determine whether the areas which were identified at an early stage as 'critical' (places where the plastic 'sits on' the metal; see Fig. 5) would be able to meet the requirements.

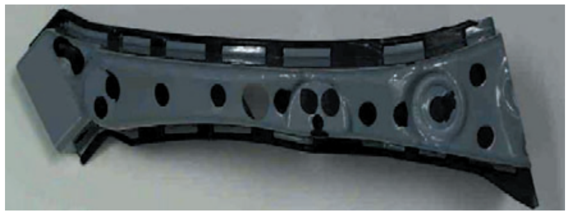

Fig. 5: Description of critical locations for the corrosion of hybrid components [1]

As part of this work, corrosion tests were carried out on the basis of Audi's internal inspection specifications INKA and P-VW 1210.
On the basis of preliminary considerations before the tests, not only were test pieces made of galvanized production sheet metal (quality St07 Z) used in corrosion testing but also sheet metal coated with Granocoat (quality DC05). The parts were manufactured using the Erlangen carrier, version 1 (dia. 32 mm), in order to ensure thorough penetration with paint in the cathodic dip painting tank and thus a complete coating of the metal surface (cf. Fig. 6).

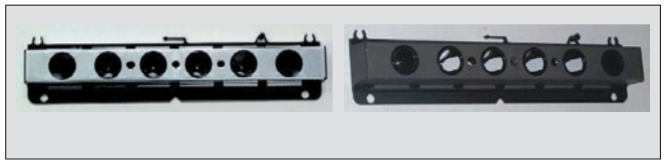

Fig. 6: Test pieces made of galvanized sheet metal (left) and coated with Granocoat (right)

In order to treat the test pieces in line with their future field of use, they were fitted to a vehicle bodyshell and following the pre-treatment processes (cleaning, phosphatizing) and priming by cathodic dip painting, removed from the process chain. With the cathodic-dip-painted hybrid components (see Fig. 6) the corrosion tests described below were carried out.

P-VW 1210

This test is a combination of:

- Saline spray test as per DIN 50 021 SS with a duration of 4 hours
- Cooling phase at room temperature with a duration of 4 hours
- Ageing under warm, humid conditions at 40 °C and 98% relative air humidity with a duration of 16 hours.

One test cycle therefore corresponds to a single day. At weekends, ageing was carried out at 18 to 28 °C and 40 to 60 % relative air humidity.
The duration of testing was defined at 30 cycles (equal to 6 weeks) [4].

INKA test

The abbreviation INKA stands for **IN**golstadt **K**orrosion and **A**geing test, which is used for both the entire vehicle as well as for small components. The INKA test is an accelerated test lasting for 5 months which simulates 12 years of exposure in the field.

With the hybrid components the following test for small parts was carried out (one pass-through corresponds to one cycle) [5]:
Constant humidity at T = 50 °C and 98 to 100% relative humidity with a duration of 29.25 hours
Constant coldness at T = -5 °C and a duration of 3.5 hours (humidity not controlled)
Saline spray mist at T = 35 °C and 100% relative humidity and a duration of 3.5 hours
Rest phases at room temperature (due to moving between test chambers)

Results and discussion

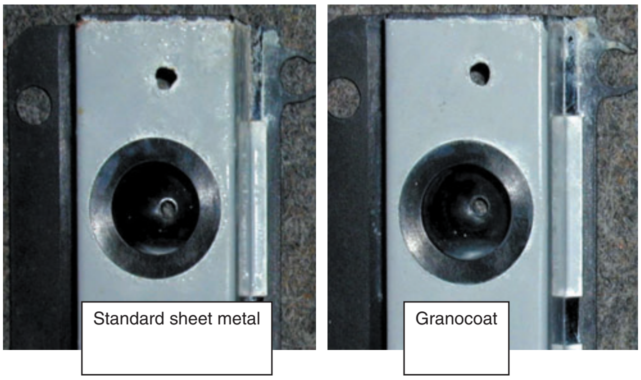

Fig. 7: Erlangen carriers after corrosion testing [1]

In both corrosion tests, compared with Granocoat components, hybrid components of standard sheet metal consisting of galvanized steel (St 07 Z) showed considerably more advanced corrosion on the upper side, particularly in the area of the plastic connections (more widespread and more pronounced undermining → rust bubbles; cf. Fig. 7).
Neither after 30 cycles nor after 60 cycles were the limits exceeded for undermining at the cracks. At those locations at threat of corrosion (in the vicinity of the through-moulding points) no occurrence of bubbling or undermining was noted (cf. Fig. 7 also) which meant that the corrosion properties could be assessed as positive.
The hybrid components made using series-production sheet metal were assessed as 'approvable' for the installation location of the roof frame (dry section → "little exposure to corrosion") by the responsible corrosion department. Approval itself always takes place at the vehicle [1].

Component-specific requirements

Material-specific requirements

In the case of Durethan BKV (as is the case with all polyamides) it should be noted that its properties are determined by the *crystallinity* as well as by the *moisture content* (this has an effect on the forces between the chains).
In order to take into consideration the influence of the moisture content in practical conditions, polyamide 6 mouldings were repeatedly subjected to the process of *conditioning* – in other words, before being used, the parts are brought up to the moisture content which is to be expected in their service environment [1].

To check the effects of the different environmental influences on the properties of Durethan BKV 30 H 2.0 and thus on the hybrid component, various drop tests were carried out at Bayer.
As can be seen from the illustration, the property changes in Durethan have serious impact even in the hybrid component and need to be taken into account in component design.
A description of the test procedures and the results of the different drop test series goes beyond the remit of this paper. However, for the hybrid components there are influences which must be taken into account in component design. These include the thickness of the metal wall, the steel quality, and environmental influences such as temperature and humidity.

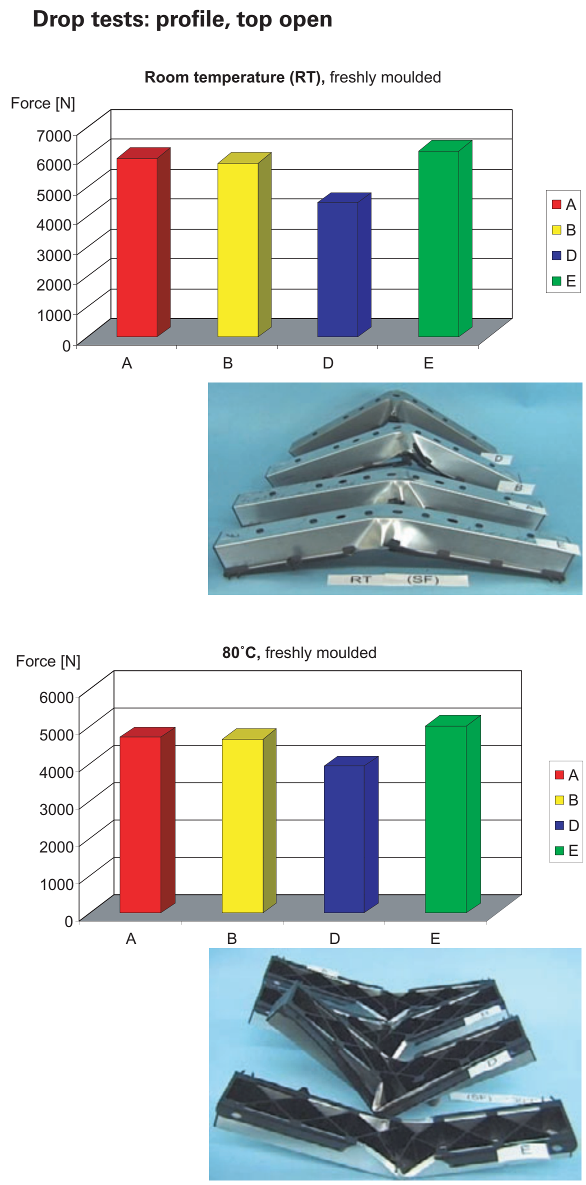

Fig. 8: Results following drop tests with Erlangen carrier [6]

Description of component

The roof frame joins the two side parts of the bodyshell and forms the support for the windscreen (cf. Fig. 9).

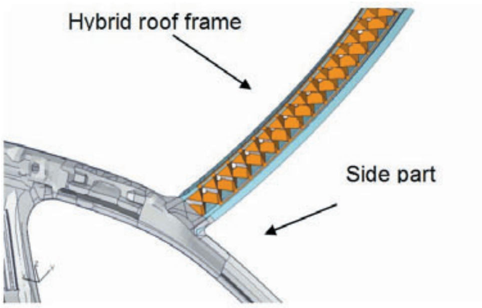

Fig. 9: Installation location of the roof frame [1]

The roof frame consists of two pieces of sheet steel which are welded together to form the profile shown on the left in Fig. 10 (double-shell sheet metal structure). With the aid of hybrid technology the sheet metal required for reinforcing the roof (against denting or buckling) is replaced by an injected ribbed structure made of plastic (see Fig. 10, right).

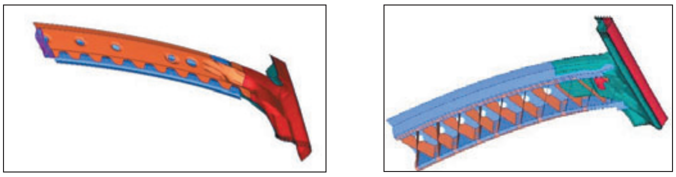

Fig. 10: Roof frame with double-shell sheet metal structure (left) and in hybrid design (right) [1]

Body rigidity

In the calculation model for the Audi A4, the two-shell roof frame was replaced by a hybrid roof frame and the calculation of body rigidity carried out again.
The hybrid roof frame solution was assessed as of equal value to the conventional solution.

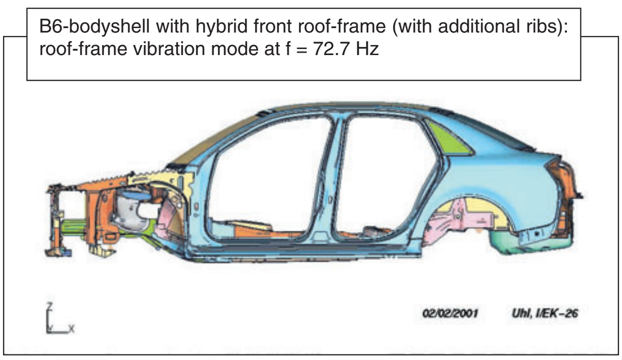

Fig. 11: Calculation of body rigidity [7]

Roof crush test

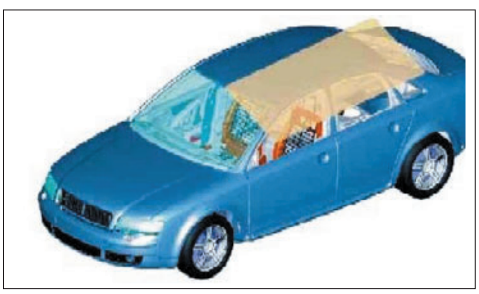

Fig. 12: Roof crush testing [7]

The quasi-static roof crush test corresponding to the US statutory instrument FMVSS 216 is used, alongside other test arrangements, for verification of roof strength. Here a steel plate is driven obliquely into the roof structure. The roof structure must exhibit a certain minimum resistance to this. In addition, Audi has some further requirements in the test as regards the minimum energy absorption and deformation characteristics.

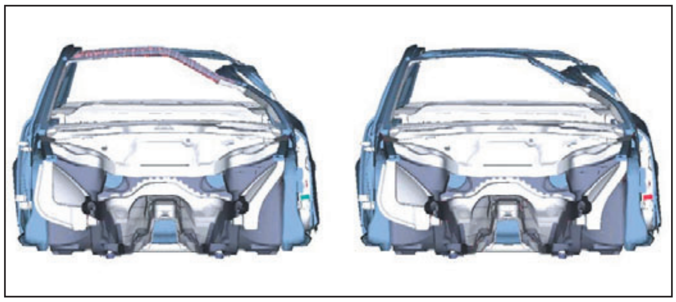

Fig. 13: Results of the roof crush loading case [7]

In the same way as with body rigidity, the calculation model was used with the roof crush criterion. Here, too, the results did not exclude development of the roof frame for series production [7].

Comparison of weight and costs

The prime objective in a possible use of the hybrid technology in the bodyshell will be a reduction in weight. The measures required to achieve this will always, however, need to be economically acceptable. For this reason, at the start of any planned development work, a rough estimate should always be made of the anticipated weights and costs.
During the course of this work, an analysis of this kind was carried out for the model of the Audi A4. Here an assessment was made on the one hand of the current series-production technology and on the other hand (comparatively) of the hybrid technology we have described. The costs and weights used in the analysis of the series-production technology were taken from the current B6 model. Relative comparisons were put into diagrammatic form for both costs and weights whereby the value 100% always applied to the current series-production technology [8].

Comparison of weight

It can be seen from Fig. 14 that when the roof frame is designed on the basis of hybrid technology a weight saving of 30% in comparison with current series production can be achieved.
The 'reinforcement' in the hybrid component which takes the form of plastic ribs corresponds to the lower sheet-metal shell of the series-production component. For the hybrid technology the 'sheet metal shell' means that part into which the plastic reinforcement is injected. The design (shape, material, wall thickness) and thus the weight was adapted to the technology being used (for example, thinner sheet-metal shell).
The value 'reinforcement' in series production in the case of the roof frame means the 'upper part' of the double-shell

structure, while 'sheet-metal shell' corresponds to the 'lower part'.

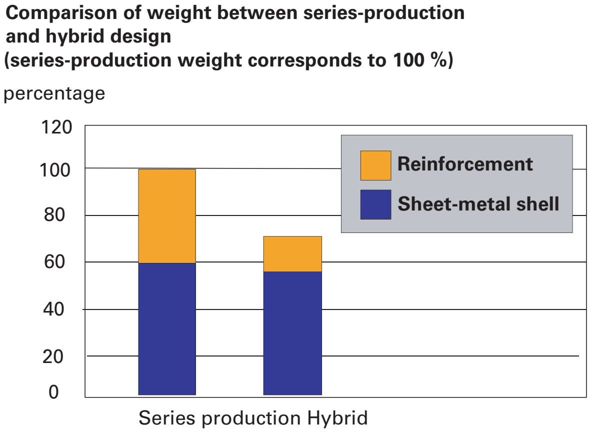

Fig. 14: Weight comparison for front part of roof frame [8]

Comparison of costs

The unit price for the technologies under consideration here are made up of the cost blocks 'sheet-metal shell' (costs for the sheet-metal part required in each case), 'reinforcement' (costs for the corresponding reinforcement) and 'investment' (Fig. 14). For the 'investment' cost block the investment costs required (delta consideration) – for example, for tooling, plant, logistics – were grouped together and recalculated for the unit part on the basis of quantity produced per part lifetime (1.5 million).

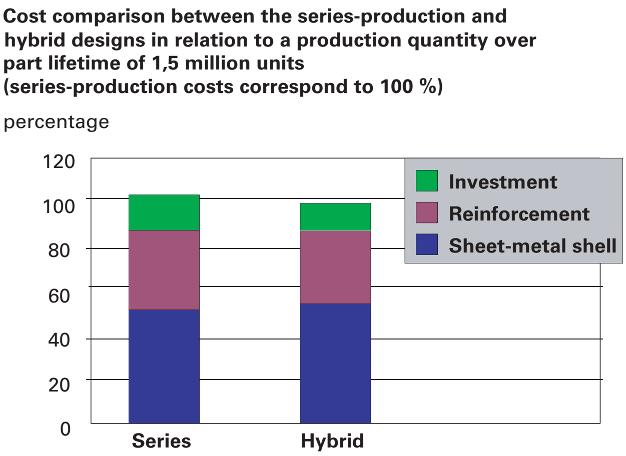

Fig. 15: Cost comparison for front section of roof frame [8]

Summary of results

With the roof frame manufactured using hybrid technology, the elimination of the top sheet-metal shell by substitution of plastic reinforcement means a weight reduction can be achieved per part and vehicle in the region of 30% (Fig. 14). With regard to costs, on the basis of this rough preliminary estimate we may assume that the part prices will remain the same (see Fig. 15). All in all it appears to make very good sense indeed to change the roof frame over to hybrid technology on account of the high savings in weight [8].

Evaluation for the production division

Following an evaluation carried out in collaboration with Audi technical departments, it would appear that with the Audi A4 a weight saving of 300 g per vehicle would be possible without affecting costs.

Furthermore, in the production division, changing over to the single-shell component design would mean savings in shop floor area of 130 m^2 as well as € 500,000 of investment. By integrating RPS points in the plastic, a reduction in tolerances is possible.

The potential for assembly operations was not at this point taken into consideration (integration of sun-visor bearings, cable attachments and so on). In bodywork construction no extensive changes are necessary since hybrid components are handled in the usual manner and can be designed as a welding group [8].

Implementation and boundary conditions in the new A6

Once the theoretical verification had been obtained for all critical points, from the point of view of the time schedule the Audi A6 appeared to be the next vehicle where changing the roof frame over to hybrid technology made sense.
It was possible to satisfy the following boundary conditions:

- Investment in test mould for design stage A
- In-vehicle testing in the first prototype vehicles with components close to series production state
- Back-up solution of two-shell sheet-metal design matured and implementable at short notice
- Inclusion of the SE group, close collaboration with raw material producers, design department and toolmakers: everyone in the same boat
- Moulds for design stage B and series production from a single source
- Inputting of all revisions and series-production data into component development

In the first design stage for the new Audi A6, hybrid roof frames close to the series production state were fitted and tested. Following positive testing results and proven neutrality with respect to costs and also weight-savings of 500 g per vehicle, a decision was taken by the SE group to use the roof frame in design stage 2 and series production.

Figures 16 and 17 show the current construction state.

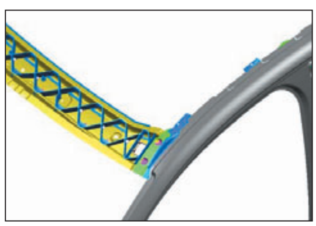

Fig. 16: View from above

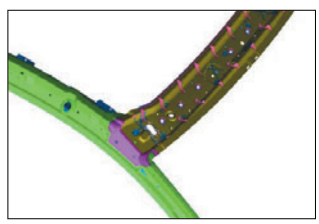

Fig. 17: View from below

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Reprint from VDI-Report No. 4261 (2004), pages 25 – 45.

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