Manufacturing and Characterisation of High-strength Plastic-metal Hybrids

Metals and plastics have long since been rival materials when it comes to "plastic substituting metal". Well-known exceptions to this rule include insert and outsert technology. This is primarily based on integrating locally arranged elements of the single material component into associated structures of the other material.

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Load-bearing, multifunctional plastic-metal hybrid structures, which are produced by injecting plastic around large-scale sheet-metal structures, use both materials in equal measure and combine their material and technical production advantages in the process. Overmoulding is a procedure involving both casting and assembling. The synergy behind these hybrid structures is what paves the way for enhanced lightweight construction outcomes in the form of unique sheet-metal structures or unique ribbed plastic structures.

Plastic structures verifiably boost the performance of metallic designs by optimally transferring the forces exerted into the component and distributing them within the same. The high elasticity of plastic means that plastic-metal compounds also excel when it comes to absorbing impact stresses. For all these reasons, plastic-metal hybrid structures also offer clear cost and weight advantages when compared to similar purely metallic equivalents, and the greater the extent to which the additional functions are incorporated into the component, the more prominent the benefits mentioned.

Meanwhile, production applications are prioritised by the automotive industry (dashboard supports, front-ends etc.) and are set

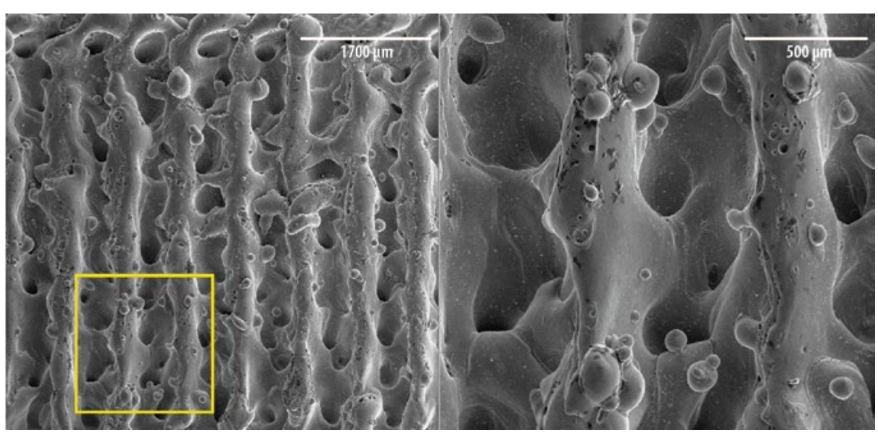


Figure 1 Laser-structured steel surface (© TRUMPF)

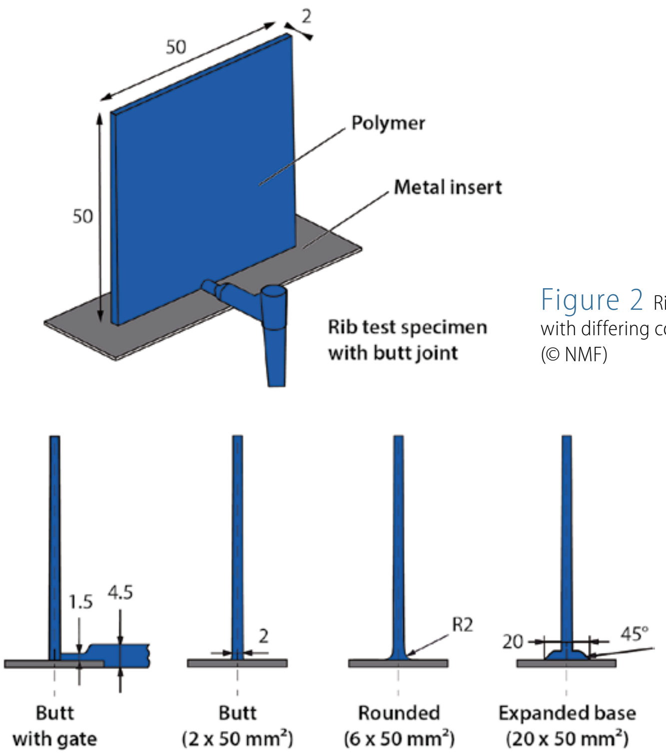


Figure 2 Ribbed test items with differing connection geometries (© NMF)

to be key components of large-scale serial production within this industry in a couple of decades' time. One thing most applications currently in serial production have in common is that the bond between the metal and plastic is via a form closure, for example through- and circular injections at boreholes and beads.

Applying High-strength Plastic-metal Composites

Investigations by Zhao [2], which were conducted at the Chair for Plastics Technology of Erlangen-Nuremberg University, clearly show the potential offered by plastic-metal hybrid structures, provided an extensive adhesive bond can be established between the plastic and metal in question. Both rigidity and strength are significantly enhanced as a result of the adhesive bond. There was also scope to boost bending and torsional strength by around 45 % compared to conventional design (selective form closure over boreholes and beads). Torsional rigidity in particularly was even doubled. This large-scale adhesive bond prevents both any buckling of the thin-walled metal sheeting and any reciprocal movement between the plastic and metal components. The adhesive bond was established through the efforts of Zhao by heating up the sheet metal up to the melting temperature range of the plastic components. However, the adhesive bond failed when exposed to alternating temperature stresses.

Current developments in the hybrid technology field targeting a permanent adhesive bond are focused on developing primer layers to facilitate adhesion (Hybrid-Plus [3], HyLight [4]) or replacing the metallic components with so-called organic sheets, namely fibre-reinforced thermoplastics [5].

Inserts to boost adhesion by adding a microstructure to the metallic components were systematically investigated as part of the ExtraLight research project. The structuring of the metallic components was undertaken as part of efforts to generate an undercut topology. During processing, the plastic penetrates the undercut areas of the metallic components and then links up with the same via a microform closure.

Laser-structuring of the Metal Sheets

To generate the undercut structures required and implement the process in an energy-efficient manner, an approach combining melt and vapour ablation – a method also used for cutting or drilling – was selected. The melt ejection initiated by the vapour recoil pressure is harnessed here to shape the indentations.

Part of the viscous mass can become detached, in particular during lengthy laser pulses involving greater melt formation and higher intensities, and be ejected from the interaction zone in the form of droplets. High-speed imaging shows how the melt ejection is delayed during structuring with short laser pulses and actually takes place over a period equivalent to several times the actual pulse duration. The pulse durations during combined melt and vapour ablation ranged from a few ns up to a few ms. Intensities exceeding 100 W/cm² were required to allow the material to be vaporised. The processing itself was conducted using high-performance nanosecond TruMicro 7050 and TruMicro 7240 lasers.

Undercut structures could be produced on steel with cladding rates of between 0.2 and 1.25 cm²/s (speed of 20.8 mm/s for a 6 mm structural width). One example on steel is shown in Figure 1. For aluminium even higher cladding rates of up to 3 cm²/s could be achieved.

Characterisation of Plastic-metal Composites

For the purpose of characterising plastic-metal hybrids, a test body was designed to allow testing of adhesive strengths within a wide strength range and under a range of different stresses. This so-called ribbed test body comprises a sheet section 40 x 70 mm in size on which a plastic rib is applied during the injection moulding process. In the process, the following can be varied:

- thickness of the sheeting, within the range 1 to 2 mm
- geometry of the rib (thickness of 2 or 4 mm)
- connecting geometries of the rib (base geometry).

The test body and the variations of the base connection are shown in Figure 2.

The first step when manufacturing the rib test body is to fix the sheeting onto the fixed mould side using mechanical clamps until the movable mould side accommodates the fixing of the sheeting via a spring-loaded insert when closing. The spring-loaded inserts accommodate any desired sheeting thickness within the range of 1 to 2 mm. The mould has three cavities. The variable gating system allows simultaneous or serial filling of cavities, allowing the impact of a range of flow conditions to be assessed.

The middle sheet-insert station can be inductively heated via a coil incorporated into the mould. The inductive heating to the desired temperature takes place within a few seconds and can also be maintained during the injection and holding-pressure phases. Any deviation of temperature from the configured target figure in the area of the connection will be limited to a few Kelvin, Figure 3.

The heating of the sheet inlay prevents premature freezing of the plastic melt and facilitates the process of filling the undercuts with the plastic matrix. Since the undercut structures are relatively large, with dimensions measured in tens of millimetres, it is also possible for for fibres from fibre-reinforced plastics to ingress into the indentations, Figure 4.

The process of characterising the front pull-off and shear strengths involves clamping sheeting and plastic rib in the relevant testing devices with a defined level of torque and initiating movement of the elements relative to each other at a speed of 2 mm/min until the point of failure. The tests were conducted at -40 °C, at room temperature and at 80 °C (PP) or 90/100 °C.

The results allow, first and foremost, a comparison of various material pairs under a range of different processing conditions. Figure 5 shows the impact of sheet preheating for sheet inlays made of steel, aluminium and magnesium. What emerges is that magnesium and steel sheets benefit more from preheating of the sheets than aluminium. This is attributable, among other things, to the better undercut structurability of the aluminium sheeting.

In addition, the failure stresses determined using this approach in the separately exerted loading directions were used as the basis for the complex geometries of the simulation.

> Both rigidity and strength are significantly enhanced as a result of the adhesive bond.

"Berlin Test Beam" Demonstrator

In real components, complex multiaxial stress states act on the points where the metal and plastic elements are joined. To take this into account, a test component was developed, the so-called "Berlin test beam", which exhibits complex geometry compared to the ribbed test body, but for which bending and torsional tests can be performed using comparatively simple means.

The Berlin test beam uses experiences gained from structures in widespread use (for example "Erlangen test beam"), but also incorporates a unique design feature: Only the frame sections are metallic, meaning the composite relies exclusively on the bond between plastic and the metal. Here, forces are only transferred between the metal and plastic components via adhesive or microform closure, with no through-injections or injections around the metallic components, Figure 6.

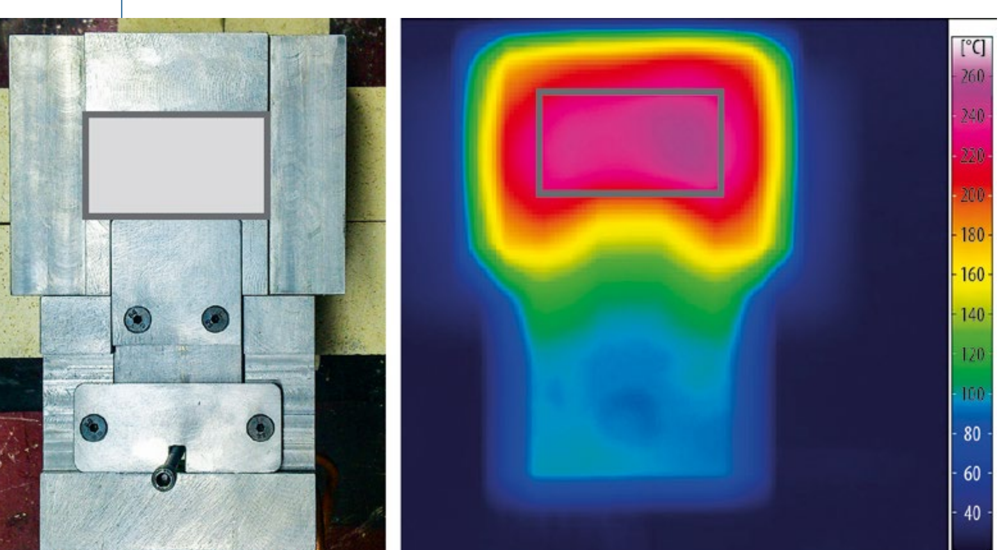


Figure 3 Temperature distribution in the middle cavity during induction heating (© NMF)

ExtraLight

The "ExtraLight" research project focusing on the topic of "Multimaterial systems – future lightweight construction for resource-saving mobility" was required as part of the "Material innovations for industry and society – WING" framework program of the German Federal Ministry for Education and Research (BMBF) and supported by the VDI as project sponsor, funding code 03X3037. Companies involved included Albis Plastic GMBH, Allod Werkstoff GmbH & Co. KG, Audi AG, BASF SE, Daimler AG, inpro Innovationsgesellschaft für fortgeschrittene Produktionssysteme in der Fahrzeugindustrie mbH, Neue Materialien Fürth GmbH, SABIC Innovative Plastics, Technische Universität Berlin, thyssenkrupp Steel Europe AG, TRUMPF Laser- und Systemtechnik GmbH and Volkswagen AG.

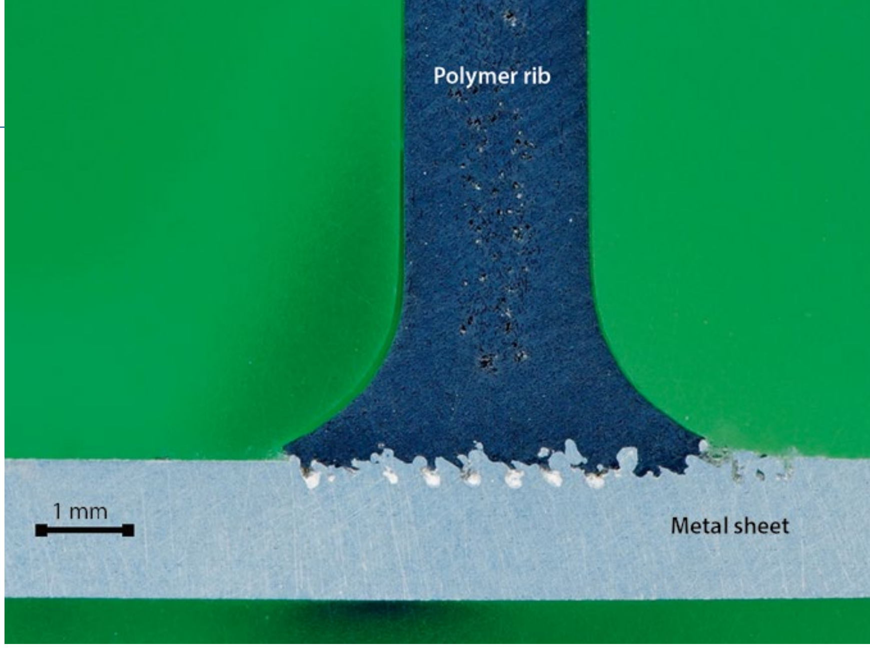


Figure 4 Transverse microsection through a ribbed test body (PA6-GF30/aluminium, rough structuring) (© NMF)

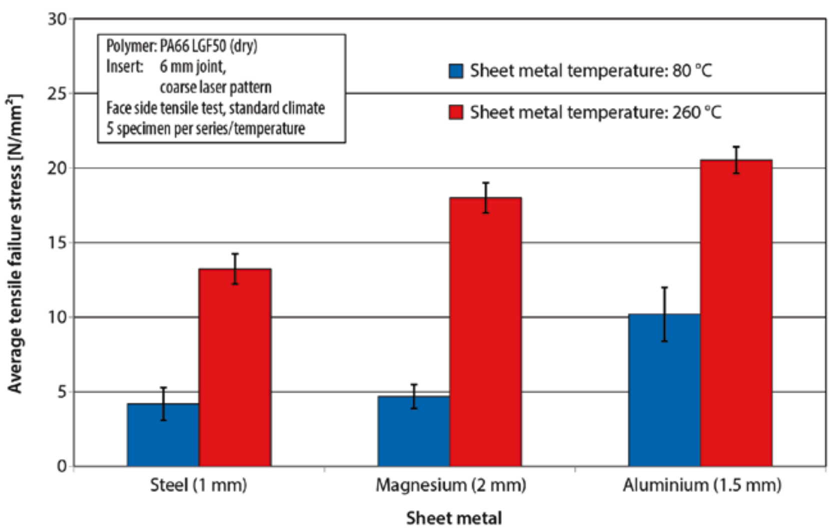


Figure 5 Impact of sheet pre-heating on steel, magnesium, aluminium (© NMF)

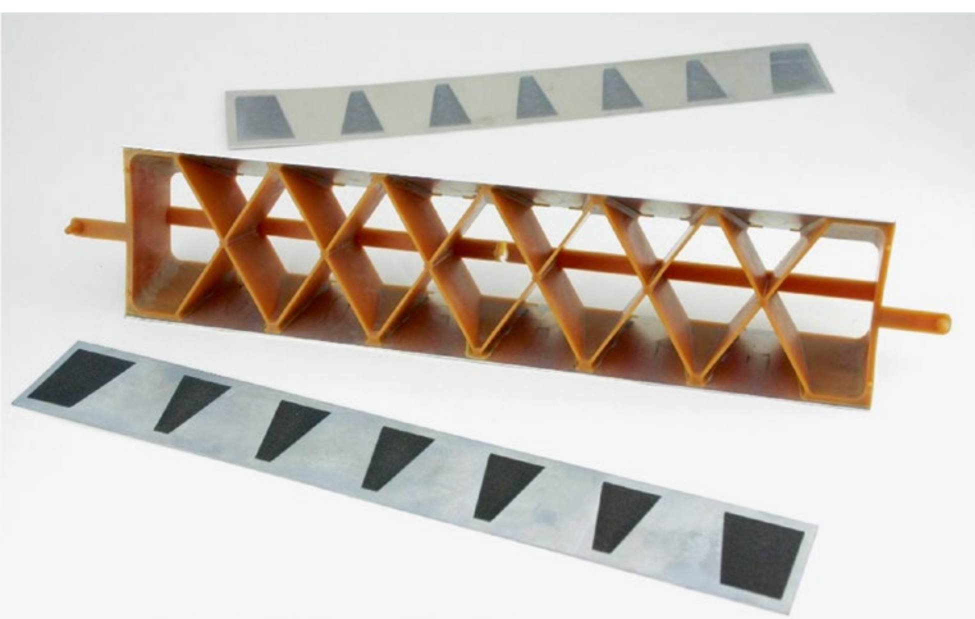


Figure 6 Laser-structured sheets and "Berlin test beam" (© NMF)

The mould includes a triple heat runner. The gating points can be used individually or in combination, allowing the impact of a range of filling scenarios on composite strength to be tested. Open nozzles are also used, to minimise any damage to the fibres for long fibre-reinforced plastics. As with the ribbed mould, there is also an option to heat up the inserted sheets via a mold-integrated induction heater to the desired temperature.

Tests on the "Berlin Test Beam"

The tests on the Berlin test beam were performed at room temperature. A first torsional test series showed that the bond between the polymer core and the external sheets was the decisive criterion dictating the overall rigidity of the component. Figure 7 shows the structure and clamping in the torsional test. The focus in developing the clamping was to ensure clamping that would minimise stress in a macroscopically deformation-free state. This prompted the selection of an inherently rigid construction, which allowed the test beam to fall inwards and prevented shear deformations at the end sections in the process. Figure 8 shows the results of torsional tests on the various components and a comparison of the complete Berlin supports. The plastic used in this case is an LNP VERTON RV00AESP (PA66LGF50) from SABIC, hereinafter abbreviated to Verton, and the aluminium is AlMg3, 3.3535 with sheet thickness of 1 mm.

It is visible that the sheets, in themselves, have only minimal torsional rigidity and the polymer core is similarly torsion-flexible, albeit at a higher level. If both components are twisted at the same time, but without bond between them, then the resultant torsional stiffness is basically an addition of the single components stiffnesses.

If a bond between the polymer and metal is generated, it results in completely different load deflection curves with far higher torsional rigidity, and failure only occurs when a large torsion angle is reached. Also on video recordings, it proved impossible to ascertain whether this was due to the metal buckling or, the plastic becoming detached from the

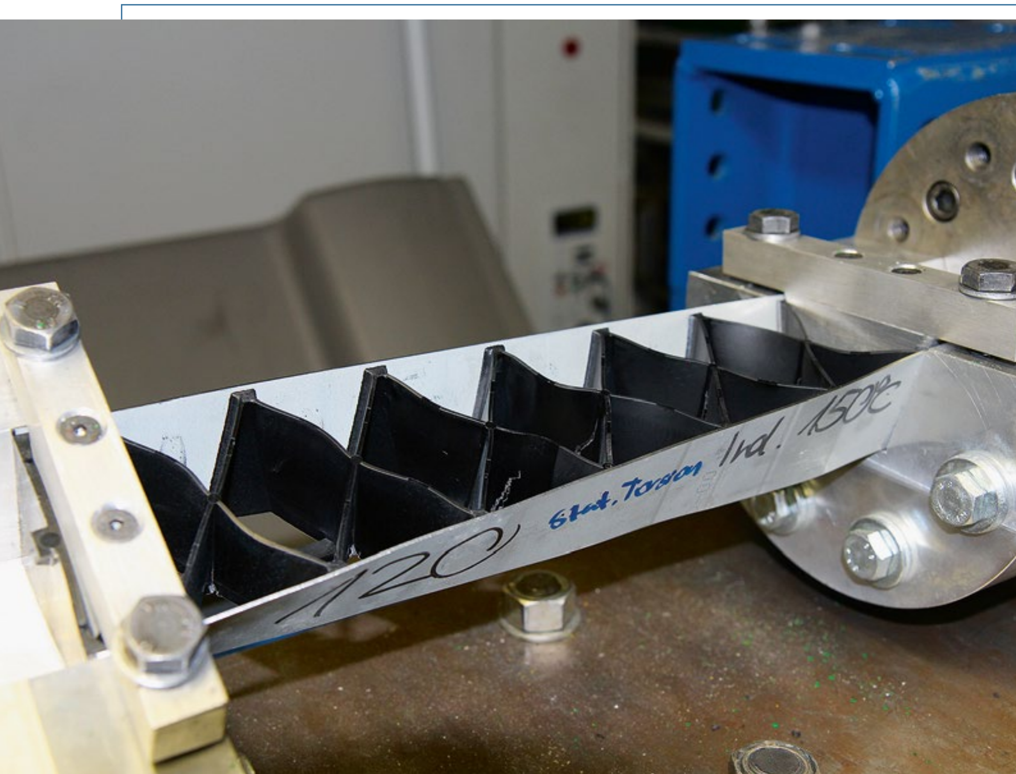


Figure 7 Structure of the torsion test for the Berlin test beam, where the failure of the ribbed section can be clearly seen (© inpro)

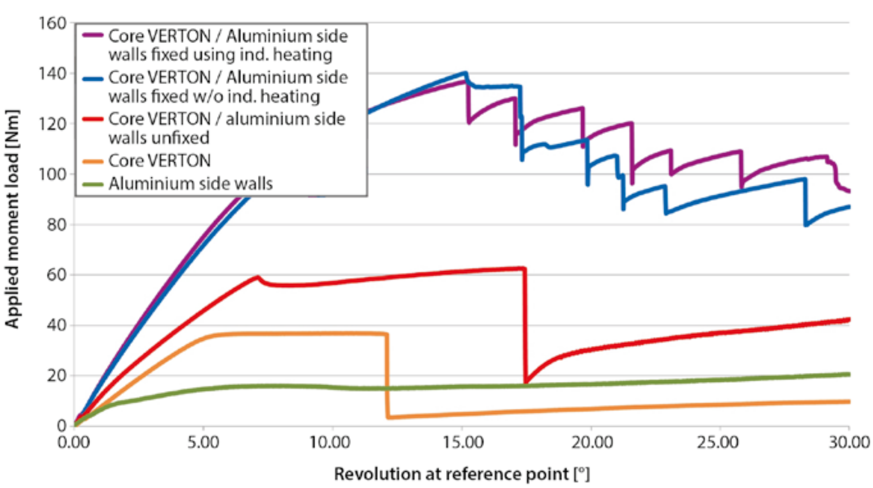


Figure 8 Torsional results for the individual components and the overall Berlin test beam (© inpro)

metal or cracking in the plastic. Even at large torsion angle, the remaining residual strength is higher than for the undamaged and unconnected individual components.

A four-point bending procedure was implemented for the bending tests on the Berlin test beam, whereby the punch was realised using a cuboid. Immediately after applying the initial load and with the initial deformation that followed, contact between the punch and the Berlin test beam only remains at both edges. Both the rotational support as well as the punch act on the polymer and prevent any peeling effects. During these tests, the free length between the supports was 250 mm and the total length of the supports was 350 mm.

The deformed test beam in Figure 9 shows that the bond between the metal and plastic has remained intact in this case, too. The metal has deformed significantly, and fractures are apparent on the underside of the polymer at points at which the stretching capacity has been exceeded. After the load peaks (initial buckling of the metal), the load declines, while additional and greater declines are caused by additional buckling as well as fractures in the polymer.

> The results allow, first and foremost, a comparison of various material pairs under a range of different processing conditions.

Applications in Trials, Transfer to Demonstrator Cockpit Crossbeam

The applicability of ExtraLight technology was investigated on a current hybrid component of the MFA1 platform and compared with the production state. The component in question is a cockpit crossbeam, featuring a plastic-metal hybrid construction (PA-GF60/Al), Figure 10. The integral connection formed between the plastic and the metal is established as part of a production process with a copolyamide hot melt (Vestamelt).

The necessary condition for deploying ExtraLight technology for serial production was to ensure that the structuring process could be fully automated and incorporated into the injection moulding process and to ensure that the cycle time would not be extended as a result.

To investigate the strengths, crossbeams were structured from Trumpf at two fixed positions (GEO2, GEO3), Figure 10, using a laser and then incorporated into the serial production process. The structuring process involved two different forms of structuring being applied, which differed primarily in terms of their main orientation directions (longitudinal or transverse). Part of the crossbeam manufactured was also subject to alternating thermal and mechanical stresses.

The thermal ageing process comprised accelerated conditioning in accordance with DIN ISO1110 and ten temperature change cycles, each two hours in length at RT, -30 °C and 100 °C. The rate of change of temperature was 1 K/min. Crossbeams treated in this manner were labelled "OLD". The connection surfaces of the GEO3 position were also additionally subjected to a mechanical fatigue test. This comprised torsional stresses alternating within the range -18 to 6 Nm over a total of 380,000 cycles and at a frequency of 2.8 Hz (labelled "with load").

Figure 9 Berlin test beam after the bending test: The folded external sheets are clearly visible; the plastic follows in such a manner that the bond remains intact (© inpro)

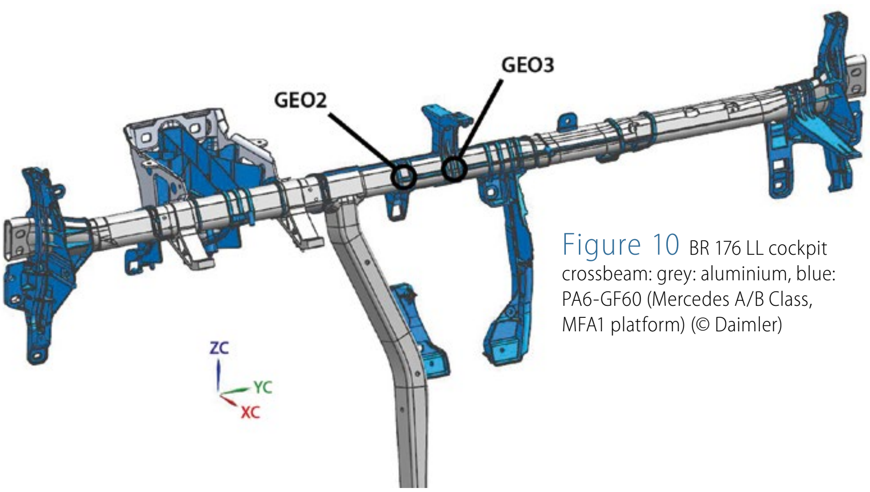
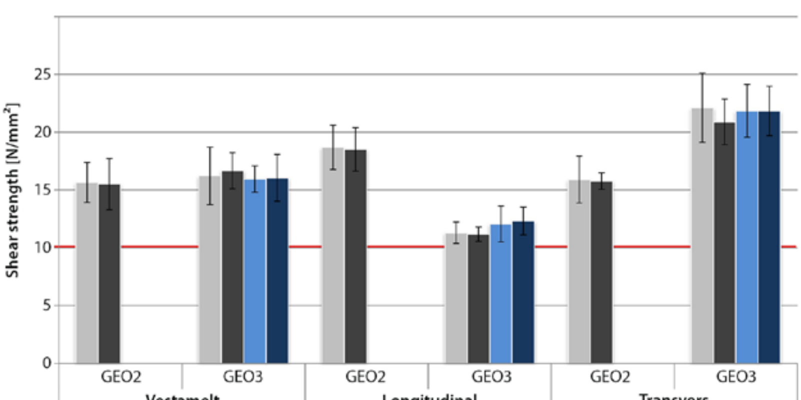


Figure 10 BR 176 LL cockpit crossbeam: grey: aluminium, blue: PA6-GF60 (Mercedes A/B Class, MFA1 platform) (© Daimler)

To characterise the mechanical strengths, circular segments were sawn out at the corresponding GEO2 and GEO3 positions and the plastic parts were sheared off in a pipe direction at a speed of 2 mm/min. Figure 11 shows the results of the shear test. All test pieces demonstrated the required minimum strength of 10 N/mm². The structuring direction also proved to have a key influence on the strength levels determined. Within the scope under consideration, thermal and mechanical stresses did not lead to any decline in strengths.



	Vestamelt GEO2	Vestamelt GEO3	Longitudinal GEO2	Longitudinal GEO3	Transvers GEO2	Transvers GEO3
No load NEW	16	16	19	11	16	22
No load OLD	16	17	19	11	16	21
With load NEW	0	16	0	12	0	22
With load OLD	0	16	0	12	0	22

Figure 11 Shear strengths of aluminium pipes subject to various structuring compared to the serial-produced "Vestamelt" at GEO2 and GEO3 positions (© Daimler)

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