Force Flux-Maintaining Spot Connections

Heavy-Duty Lightweight Structures. A hybrid construction principle for joining fiber-reinforced plastic composites and metals can be used to develop weight-optimized structures with high stiffness and load-bearing capability. For such applications, a novel joining process which maintains the force flux and, in addition, is suitable for mass production has been developed for high-performance applications.

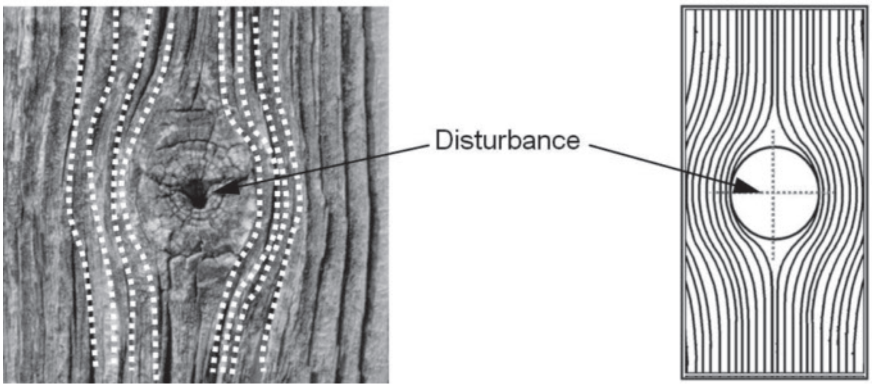

Fig. 1. Disturbance in a tree, with redirection of fibers to maintain the force flux [7]

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In the fields of machine building and automaking as well as in aviation and aerospace, increasingly demanding requirements are leading to energy-efficient processes and components with a high-performance capability for use in the development of new hybrid construction methods. A hybrid construction principle makes it possible to develop weight-optimized structures with great stiffness and high load-bearing capability. The joining technique required for this plays a central role in the manufacturing process, with low-heat processes such as adhesive bonding or mechanical joining replacing thermal techniques more and more frequently [1]. Hybrid structural solutions based on fiber-reinforced plastic composites (FRP) and metals that do not require classical joining elements offer the advantage of in-situ production without the need for subsequent assembly processes. In the automobile industry, typical examples include hybrid components such as instrument panels and underfloor elements as well as front ends injection or compression molded from short and long glass fiber-reinforced polypropylene (PP) [2].

There is an especially pronounced trend in automaking to use lightweight materials, with the current assumption being that, in the medium term, plastics will increase to a proportion of about 20 wt.-% [3]. The reasons for this are primarily the requirements to reduce CO_2 emissions. Because of their relatively low density, lower manufacturing costs when produced in volume and recyclability, thermoplastics offer particular benefits [4, 5].

At the same time, steel remains the predominant material for automobile bodies. This is where an endless fiber-reinforced composite such as thermoformable glass fiber-reinforced thermoplastic sheet stock, because of its high specific strength and stiffness characteristics, can make a significant contribution to lightweighting. Furthermore, this material provides a higher specific energy absorption capability than comparable sheet metal designs and for this reason is almost predestined for impact-absorbing applications. Taking this approach, BMW AG was able to reduce the mass of a bumper from 7 kg (aluminum) to 3.1 kg (glass fiber-reinforced polyamide 6, PA6). →

! Essential Features of the Flow Forming Connection Technology

- Lighter weight design, since in contrast to typical systems no additional supplemental joining element (screws, rivets, adhesive ...) is needed;
- Simple handling (no predrilling operation, no preparation of the materials to be joined is necessary);
- Short process times (as little as 2 s/connection);
- Highly automated, similar to spot welding;
- High-strength connection, due to redirection of the fibers and strengthening of the hole; in addition, the thermomechanically flow-formed connection provides a heavy-duty, error-tolerant system for introduction of force in hybrid high-performance structures that is suitable for mass production.

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Joining Technique for Composite/Metal Structures

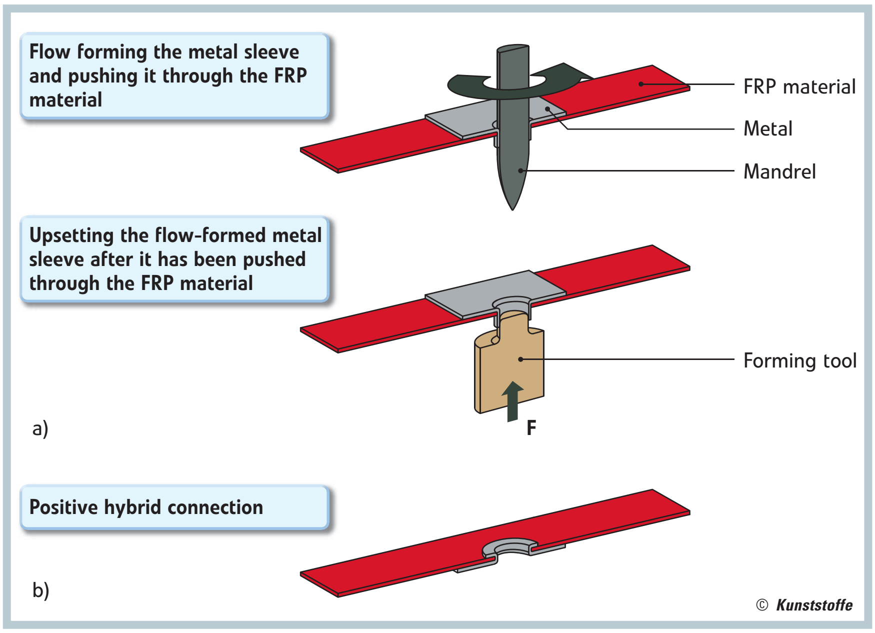
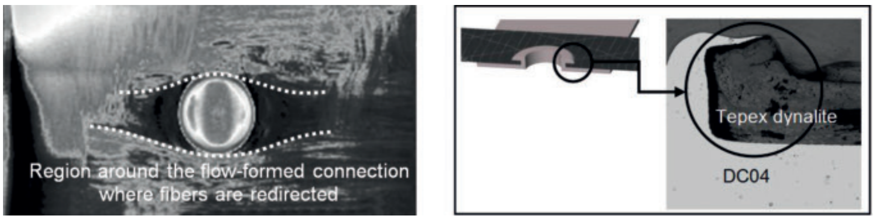


Fig. 2. Process for creating a thermomechanically flow-formed connection: a) principle used to produce a thermomechanically flow-formed connection, b) view through section [11]

Non-positive (friction-based) as well as positive connections and even quasi molecular-level joining approaches require a variety of supplemental joining elements that unavoidably contribute to an increase in component mass. In addition, the components to be joined sometimes must undergo extensive preliminary operations. These may include drilling of holes for bolted or riveted connections or activation of the surface by etching, grinding and degreasing for adhesive bonding. Drilling in particular as well as punching holes in connecting elements by means of a sharp tool result in undesirable fiber breakage in the composite at the connection point. This interrupts the flow of force (force flux) in the reinforcing fibers, which means that the great potential of the fiber-reinforced composite can be exploited to only a limited extent.

Observation of the structural principles employed in nature and how these are modified at locations where a disturbance occurs can provide guidance when it comes to designing an optimal joint. For instance, maintenance of a uniform stress distribution in the disturbed zone is observed in trees [6, 7]. If a tree sustains damage in the form or cracked, rotten or broken branches, structural weakness and the resultant increased stress can be diminished by building up material in the vicinity of the defect. **Figure 1** shows how wood fibers are redirected radially at defects (e.g. caused by knotholes) as a way to counteract the "dangerous" notch effect and in this way establish a relatively uniform stress distribution.



a) b)

Fig. 3. Phenomena occurring at the thermomechanically flow-formed connection: a) computer tomographic image (CT) of a thermomechanically flow-formed connection (DC04/PA6CF), b) microsection of a thermomechanically flow-formed connection – local thickening of the FRP component

Thermo Mechanically Flow-formed Connection

Compared to multi-piece metal structures, designing and producing a fiber-reinforced composite/metal structure is considerably more complex. This is attributable primarily to the effort needed to design a connection to the composite that is suitable for the load to be withstood. A hybrid joint that is appropriate for the composite should be economical to produce, the flow of force should follow the fibers – similar to what occurs in nature – and not increase the component weight. At present, this is possible only with short production runs and often involves complex design and technological solutions [8]. The low level of automation associated with such approaches makes the lightweight design more expensive and prevents adoption for high-volume applications [9].

The process for creating a thermomechanically flow-formed connection (patent applied for) developed at the Institute for Lightweight Structures and Sports Equipment (Institut für Strukturleichtbau und Sportgerätetechnik, IST) at the Chemnitz University of Technology [10] for joining thermoplastic FRPs and metals is ideal for economical mass production. Characterized by short process times, force flux-based and high-strength joints as well as a lightweight design, it represents a new process that can be employed in various branches of industry. Compared to conventional techniques, the primary benefit it offers is that no additional supplemental joining element is needed to connect the components. When creating such a joint, the plastic flow properties of the metal component are exploited locally. With the aid of a rotating mandrel, a sleeve is formed thermomechanically flow formed from the base material. Simultaneous with the flow forming, this sleeve is pushed through the FRP component, which is likewise plasticized locally, and is upset to create a positive connection upon retraction of the mandrel or in a subsequent operation (**Fig. 2a and b**).

By rotating the mandrel, the resultant friction is converted into thermal energy that is introduced into the FRP component locally, causing partial melting of the thermoplastic matrix. An additional device can also be used to support warming of the plastic component. This allows the endless fibers in the plastic to "move" and be deflected during forming of the sleeve, thereby maintaining the force flux (**Fig. 3a**). In addition to redirection of the fibers – in a manner similar to what occurs in nature – the joint in the FRP component is thickened locally (**Fig. 3b**).

The force flux-based structure at the disturbance, characterized by force flux-oriented lateral redirection of fibers, local thickening of the FRP component and

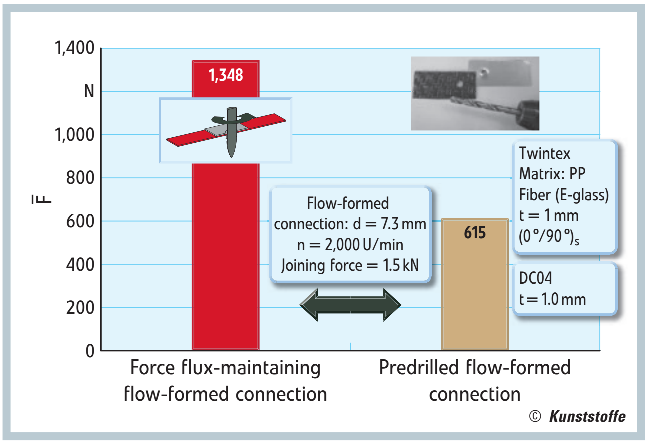


Fig. 4. Effect of force flux-maintaining and drilled thermomechanically flow-formed connections on the load-bearing capacity in a tensile-shear test [12]

increased fiber volume content directly at the joint, improves the mechanical properties of the connection noticeably. In contrast to FRP connections with predrilled holes, the number of load-bearing fibers is not reduced with the new flow forming joining process. As a result, notch and bearing stress (deformation) effects around the edge of the hole in the orthotropic FRP component be decreased considerably, which means that noticeably higher holding forces can be transmitted under both shear and pull-out loads **(Fig. 4)**.

To characterize the flow-formed connection mechanically, static shear and pull-out test based on those described in DIN EN ISO 14273 and DIN EN ISO 14272 were performed. To this end, connections between bidirectionally reinforced multi-layer PP composites and deep-drawn steel DC04 were produced. Each test specimen was tested quasistatically at a test speed of 2 mm/min. The results of the tests are compared with conventional Plytron/DC04 hybrid connections having a connected-part diameter of 5 mm in **Figure 5**.

Comparison of the holding forces of flow-formed connections measured in shear and pull-out tests with established joining methods shows the great potential of this new technology. In tensile shear tests, the connection fails primarily in response to shear fracture in the FRP component. In pull-out tests, “release” from the FRP component results from straightening of the upset metal sleeve. In contrast to what occurs under shear loads, failure of the connection is associated with the metal component. For both types of loads, however, a noticeable increase in load-bearing capacity while simultaneously reducing the mass is achieved.

Summary

Classical spot connections such as screws, bolts or rivets cause considerable concentration of stress at the point of connection in fiber-reinforced plastic (FRP) composites and reduce the load-bearing capacity drastically as a consequence of interruption of the force flux. In FRP/ metal hybrid structures in particular, the fiber-reinforced composites in the region of the connection are gen- →

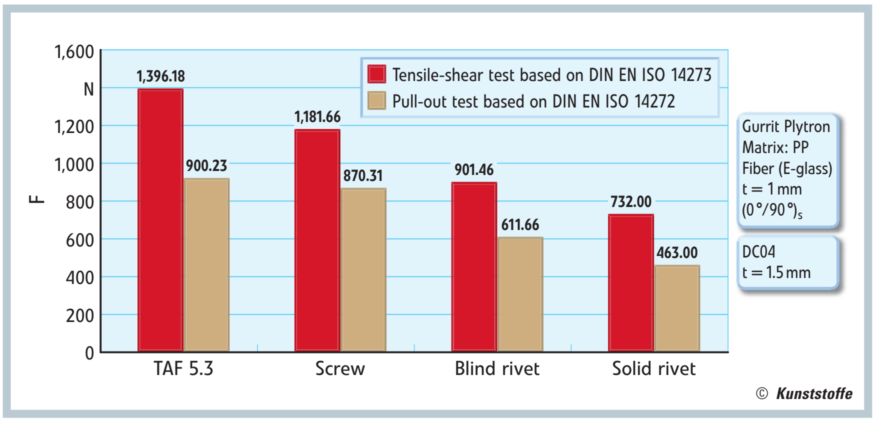


Fig. 5. Holding forces in shear and pull-out tests (TAF: thermomechanically flow-formed connection)

erally the failure-relevant structure. In order to utilize the great potential of FRP components to the maximum extent for lightweight designs instead of metallic materials of construction, it was necessary to develop a joining technique suitable for use with the fiber-reinforced composite.

The flow forming connection process represents a new approach to joining flat and thermoplastic FRP components that maintains the force flux. The technique employs a rotating mandrel to form a sleeve from the metal base material. During this process, the metal component undergoes local plastic deformation. At the same time conduction heats the FRP component, causing local melting. As the sleeve is being formed and pushed through the plastic, the now somewhat mobile fibers are redirected around the disturbance, maintaining the force flux. The subsequent controlled upsetting of the sleeve joins the two components together by a positive connection. ■

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