DOI: http://dx.doi.org/10.15407/tpwj2019.02.04

JOINING OF STEEL AND DISSIMILAR MATERIAL JOINTS WITH HIGHEST STRENGTH — THERE ARE OTHER WAYS THAN CONVENTIONAL WELDING

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Technological products are undergoing a continuous evolution, which, in many cases, require new materials and material combinations. In turn, these novel material concepts require their own special joining technology. Although classical joining methods can frequently be adapted, there are often drawbacks connected with these adaptions. Novel joining processes, such as Laser Beam Welding in Vacuum, MIG-Brazing of aluminium to steel or novel technologies for bonding steel to fiber-reinforced plastics aim at overcoming existing price or design limits and also at providing engineers with new possibilities for challenging future products. 7 Ref., 16 Figures.

Technological products are undergoing a continuous evolution driven by market demands for products that have less weight, are more energy-efficient, provide more and better functions, are smarter and cheaper or boast with new and spectacular designs. Meeting these demands is in many cases a challenge requiring new materials and material combinations, which in turn require their own special joining technology.

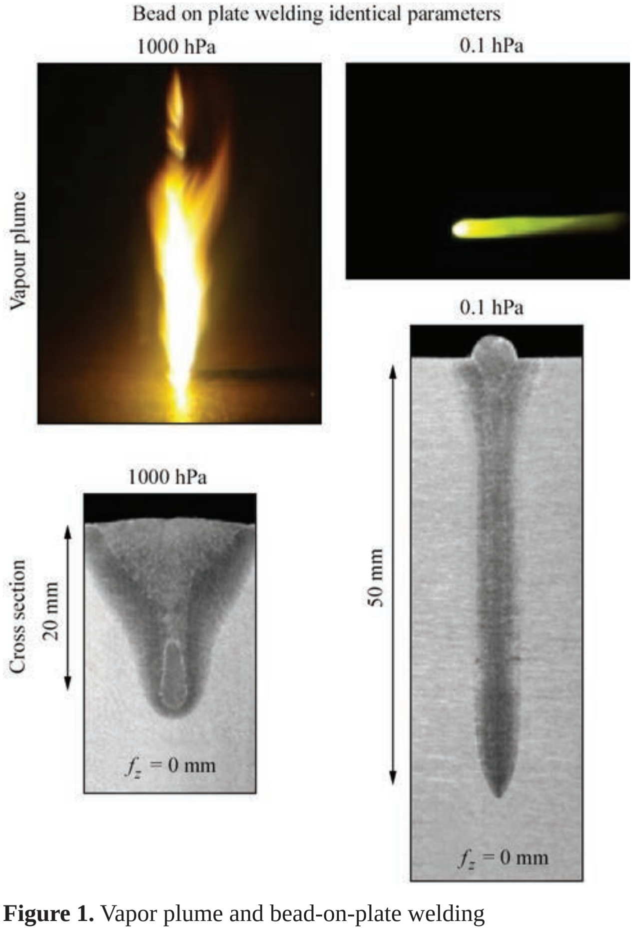

Figure 1. Vapor plume and bead-on-plate welding

Even though classical joining methods can often be adapted to meet these new challenges, there are often drawbacks connected with these adaptions, such as price and design limits. Novel joining processes, as they are discussed in this article, aim at overcoming existing price or design limits and providing engineers with new possibilities for challenging future products.

Laser beam welding in vacuum (LaVa) [1, 2]. Laser beam welding is a well-known and well-established process in industry. Therefore, laser beam welding can meanwhile be called a conventional welding process. It provides high-speed welding and low distortion for a great variety of materials. Nevertheless, the development of a large plasma plume leads to a shielding of the workpiece, thus limiting energy transfer into the workpiece and in consequence also limiting possible penetration depth.

The reduction of the ambient pressure (as far as to a vacuum) leads to an enormous change in the metal vapor plume above the keyhole and in the inner weld seam geometry. The plasma plume can be completely suppressed by the vacuum. Especially with a low welding speed, the weld seam becomes much more narrow and the penetration depth is increased by a factor of two, Figure 1. The process efficiency relating to the amount of molten material remains unaffected.

In the course of the research work of the past years, it was possible to demonstrate that the effect of increased penetration depth and narrow weld seam at low welding speeds can be transferred to deep penetration welding for industrial applications. Single-pass joint welds on a plate thickness of 50 mm for unalloyed steels and of 30 mm for high alloyed steels are achieved, Figure 2. With the double-sided single-pass welding technique, joint welds for a plate thickness of up to 110 mm have become possible. Spatter formation on the weld top side is strongly reduced, very finely rippled top weld beads can be produced and the tendency to pore formation is reduced by facilitated degassing in the reduced pressure.

Comparative studies of LaVa-welding of copper (copper with high residual phosphorus Cu-DHP) at atmospheric pressure of 1000 hPa and vacuum pressure of 0.2 hPa with basic welding parameters (focus position on the surface, without beam oscillation) prove that a significant stabilization of the welding process by the reduction of the ambient pressure is the result, Figure 3.

At a working pressure of 0.2 hPa and a welding speed of 1.5 m/min weld metal ejections can be completely avoided up to the maximum power of 16 kW. Comparative welding trials with identical welding parameters and identical equipment at a pressure of 1000 hPa show the typical welding defects. This process stabilization can also be observed at even lower speeds around 1 m/min but the welds start to develop weld metal ejections at high power levels above 12 kW, Figure 6. The latest research results prove that these process limits can be further reduced by an optimization of the welding parameters.

At a laser power level of 8 kW (multimode disc laser, spot diameter 0.3 mm) and pressure level of 0.1 hPa, welding at low welding speeds (range of 1.5 m/min down to 0.5 m/min) is possible without weld metal ejections. In comparison to welding at atmospheric pressure, high penetration depth values (5 mm at 1.5 m/min up to 8.5 mm at 0.5 m/min) are achieved with high process reliability. It can also be observed that the stabilization at the start of the welding process and achievement of the nominal penetration depth needs a distance of 5 to 10 mm, which is independent from the welding speed, Figure 4.

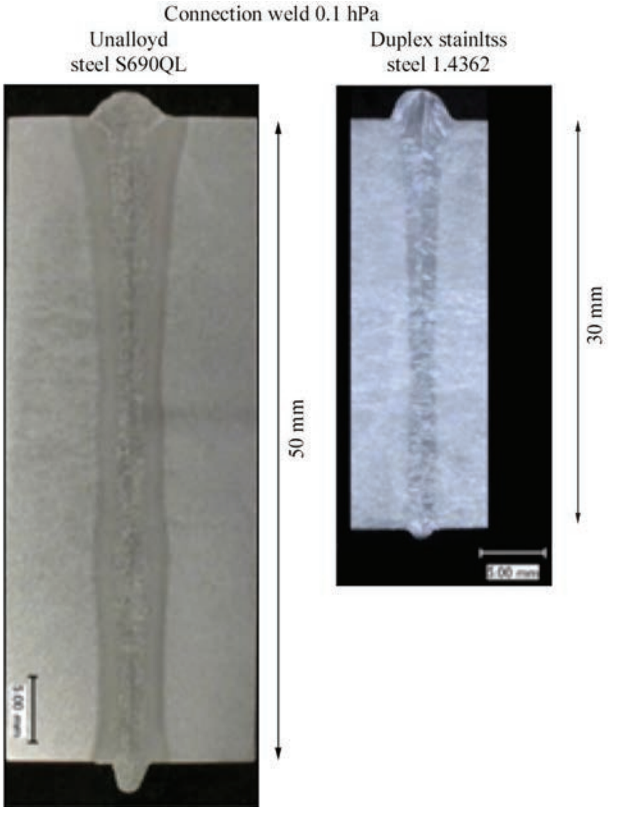

Figure 2. Connection weld unalloyed steel (50 mm) and duplex stainless steel (30 mm)

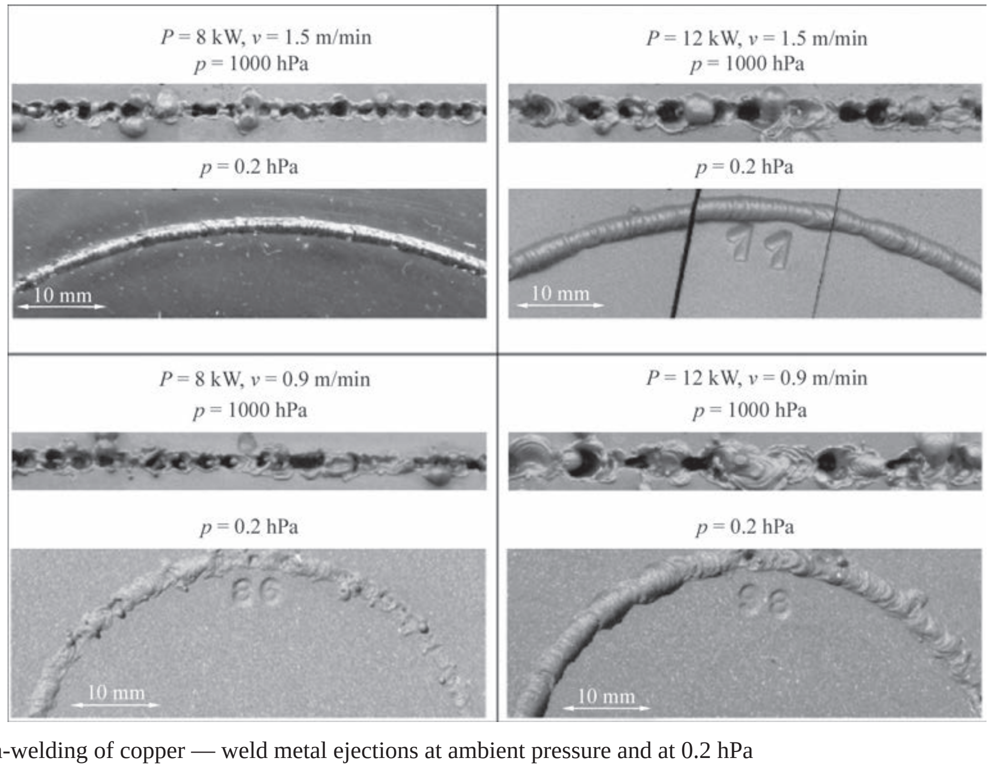

Figure 3. LaVa-welding of copper — weld metal ejections at ambient pressure and at 0.2 hPa

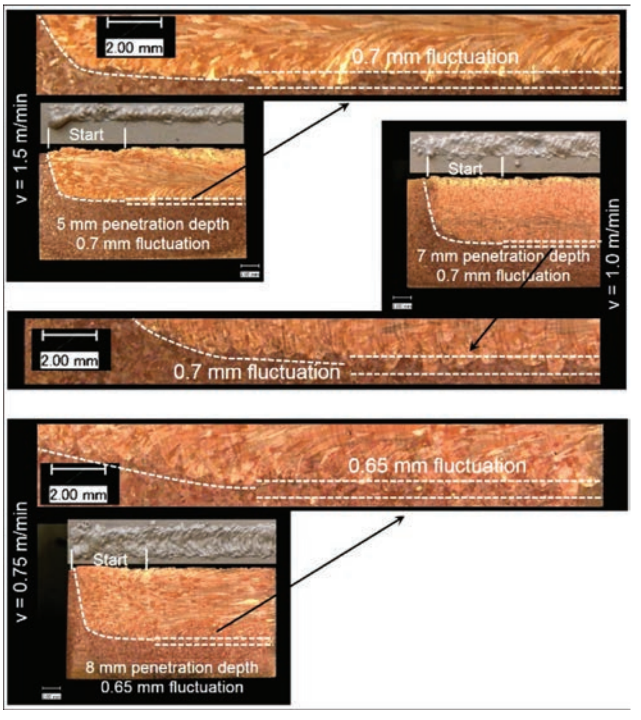

Figure 4. LaVa-welding of copper — penetration depth and fluctuation of penetration at different welding velocities

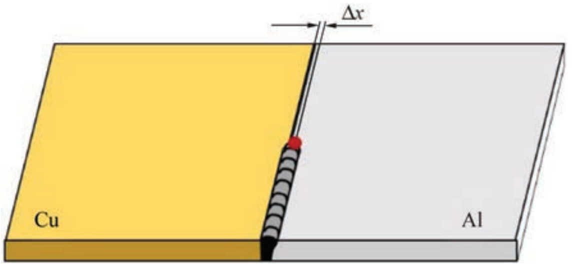

Figure 5. Schematic representation of the LBW process and focal off-set

Reducing the work pressure had a great influence on the process stability when welding copper or aluminum. For this reason and to minimize oxidation during welding the laser beam under vacuum (LaVa) process was used to weld copper to aluminum, a joint of special interest for electrical engineering. In order to change the dilution of the mixed material joint by melting less copper, the focal position of the laser beam was changed parallel to the welding direction as shown in Figure 5. Additionally, circular beam oscillation was used to influence the dilution of the joint.

Sound welds of the material combination aluminum-copper were produced using laser beam welding under reduced ambient pressure. The trials done in this work all show very small narrow weld seams with a very low content of copper. The reason for that is most probably the fact, that aluminum and copper show different absorption rates for infrared laser energy. The laser intensity and energy per unit length used in this work was high enough to melt the aluminum base material but was almost totally reflected by the copper. This presumption is supported by the fact that the fusion line on the copper side is a straight line (joint preparation) and the weld seam area increases when using a beam off-set towards the aluminum side (Figure 6). Thus, an uncontrolled formation of brittle intermetallic is avoided. The joint can therefore be described as a weld on the aluminum side and as a braze weld towards the copper joining member.

To evaluate the quality of a Cu–Al material joint, the electrical resistance Rv was measured. All connections showed an electrical resistance between that

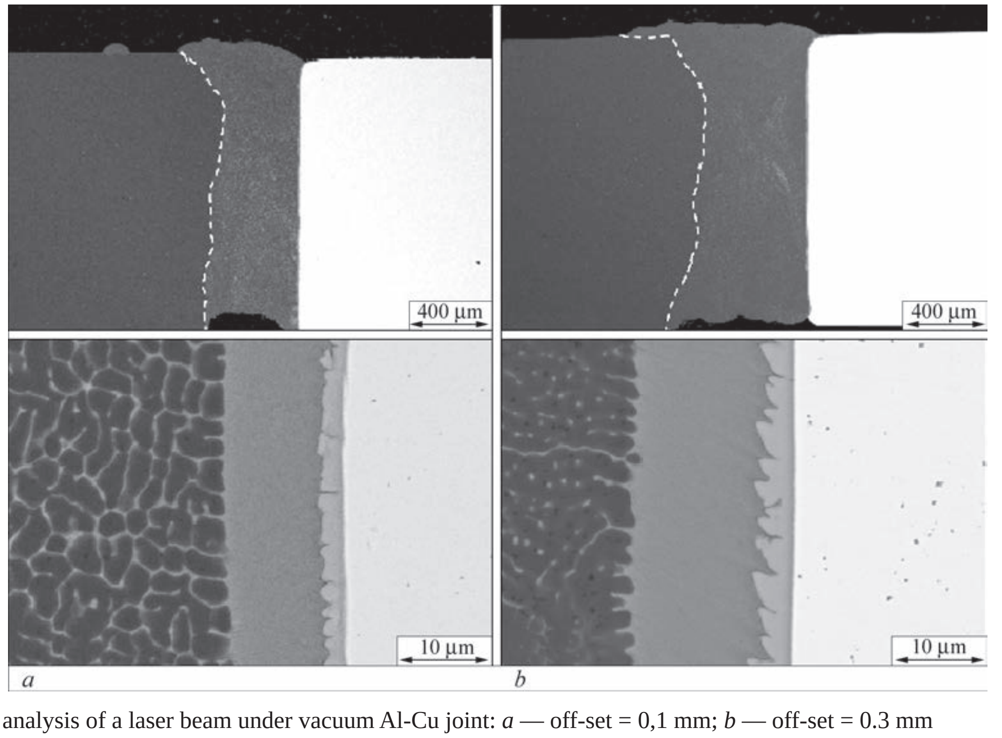

Figure 6. BSE analysis of a laser beam under vacuum Al-Cu joint: *a* — off-set = 0,1 mm; *b* — off-set = 0.3 mm

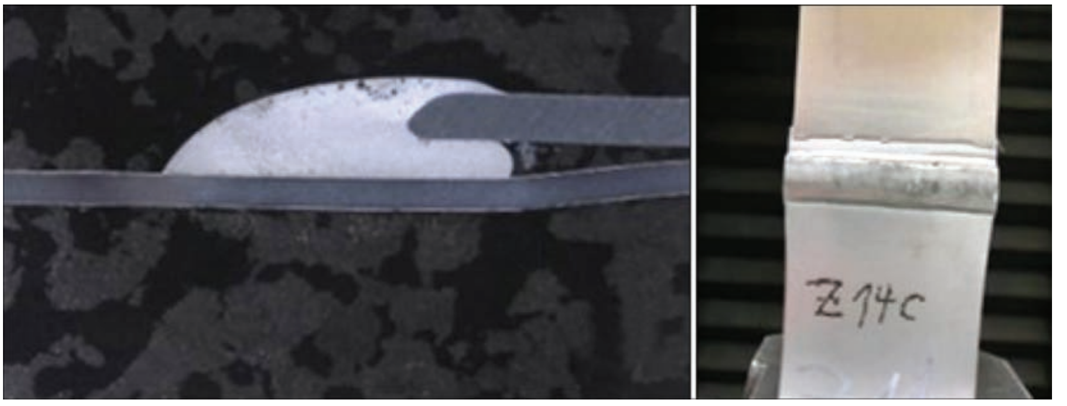

Figure 7. Steel-aluminum mixed joint with the brazing wire ZnAl4

of the base materials. A current flow of 200 A resulted in a decrease, followed by an increase of the connection resistance Rv over time. A growth of the intermetallic phase could not be observed after applying a current for two weeks.

MIG-brazing of aluminium to steel [3]. Optimised lightweight car body building often involves multi-material designs. One of the desired combinations that excludes conventional welding because of the formation of brittle intermetallic phases is the joining of aluminium to steel. For this reason joining is done, despite of the costs, mainly by punch riveting, self-tapping fasteners, adhesive bonding or other non thermal joining technologies.

Thermal joining is mostly rejected by the industry due to the challenges it presents. In addition to the different physical properties of the two materials, such as heat conductivity and thermal expansion, the metallurgical incompatibility of steel and aluminum results in the formation of intermetallic phases during and after the joining process. Arc brazing processes using a zinc based wire have the potential for use in thermal joining of steel and aluminum, pursuing a lightweight strategy through multi-material design. Different from the use of aluminum-based wires where the brittle intermetallic phase layer emerges in form of a continuous seam along the steel-aluminum interface thus making this area susceptible to crack development and propagation, the use of a zinc-based wire allows to avoid the continuous formation of the intermetallic phases. This way, the negative impact of intermetallic phase formation on the mechanical properties of the joint is limited.

Compared with steel and aluminium, zinc-based brazing materials have a lower melting point which allows to reduce the heat required for the joining process and thus also the accompanying distortion of the component. Moreover, less heat influence on the base materials and the surface coatings is also possible. As in joining of steel-aluminium dissimilar material joints with aluminium-based brazing wires, the joining point is brazed on the side of the steel and welded on the aluminium side. So far, a great challenge when applying different arc processes has been the low melting temperature of zinc which has a negative influence on the arc stability. Due to the controlled arc processes, the heat input and the droplet detachment is modified in such way that the arc is used as local heat source and, at the same time, it is possible to achieve a defined and sufficient deposition of molten filler material into the joining zone.

Among other things, overlap joints on hot-dip galvanised steel sheets DX 56 with a thickness of 1.0 mm and on aluminium sheets EN AW 6016 T4 with a thickness of 1.15 mm were carried out. With sufficient wetting of the steel sheet, the specimen fails in the heat-affected zone of the aluminium sheet. On the side of the steel, this material combination exceeds 90 % of the tensile strength with respective constriction of the specimens, Figure 7. The zinc layer of the steel sheet is not affected alongside the seam and also not on the sheet bottom side which allows for corrosion resistance without needing finishing work. It can be shown that constant strength can be obtained for overlap joints with a gap bridging ability of more than 1 mm. This should be sufficient to tackle production

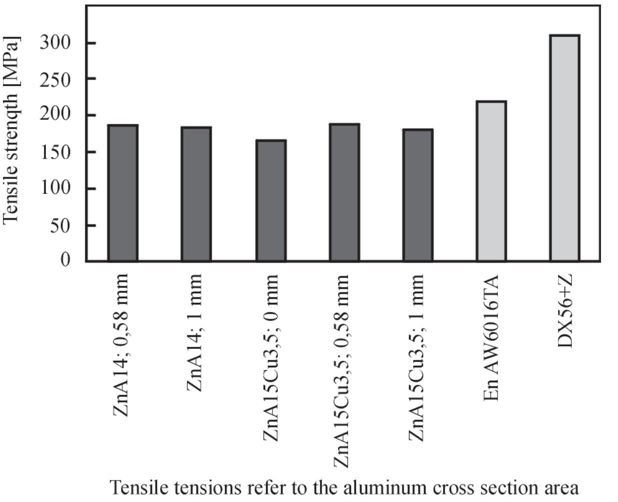

Figure 8. Tensile strength of steel-aluminum joints using different wires and defined gaps

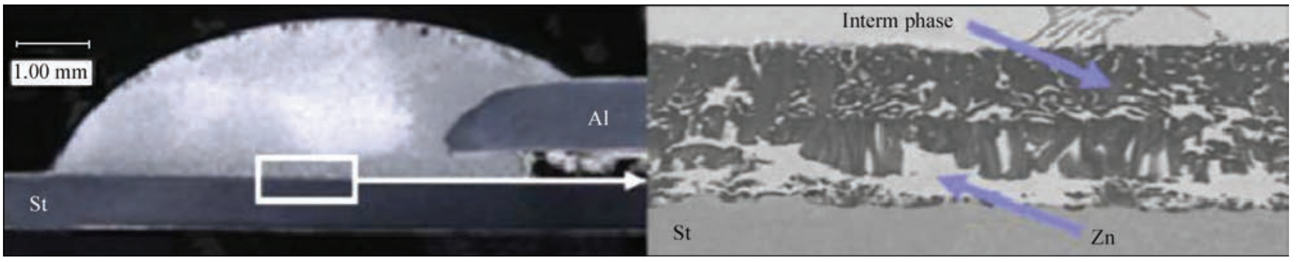

Figure 9. Intermetallic phase formation when using a zinc-based wire

tolerances that are common in practical applications, (Figure 8).

It was possible to produce steel-aluminium dissimilar joints with mechanically favourable seam geometries without the application of flux (Figure 9, left).

Metallographical examinations established that the brittle intermetallic phases are embedded in a ductile zinc matrix. Due to this structure, the negative influence which the brittle phases exert on the mechanical properties of the steel-aluminium dissimilar joints is reduced [4]. In a cooperation with the automotive industry, a demonstrator has finally been designed and constructed which shows the possibilities of the application of zinc-based brazing materials. In doing so, the same wire was used for joining steel with aluminium and also steel with steel. In both joining tasks, the strength of the base material was successfully achieved.

Joining of steel to fiber-reinforced plastics [5]. Lightweight design is constantly gaining importance in a variety of industries (aero-space, automotive, sports equipment, etc.). Materials with high specific densities, such as steel, are replaced by materials with a more favourable ratio of strength (or rigidity) to their weight like fiber-reinforced plastics (FRP). Hoewever, the favourable properties of FRP can only be fully exploited in fiber direction. Moreover, metallic materials are more suitable for the induction of complex forces and are characterized by a higher abrasive wear resistance. In order to take advantage of both materials, FRP composites need to be integrated within metallic structures. Joining metallic structures to FRP composites therefore is one of the challenge in the area of lightweight design.

Existing joining technologies for solving this task are adhesive bonding and formfitting connections, in most cases rivets or bolts. In case of failure, form-fitting elements show a ductile behavior in most cases. This leads to a high process reliability and a high user acceptance. However, this kind of formfitting connections involve recesses in the components, which require an additional process step and lead to an interruption of the fiber formation of the composite materials. This, in turn, leads to the weakening of the supporting cross-section and, due to the notch effect, to high stress concentrations close to the recess, which are almost always the source of fatigue cracks.

Adhesive bonding is a well suited connection technique which transfers the forces homogeneously into the composite and is commonly used in this field. The supporting cross-sections are not reduced and the notch effect is avoided. Particularly for hybrid connections between FRP and metals, adhesive bonding is often regarded as the most convenient procedure. One disadvantage is the sensitivity of adhesives against high temperatures and humidity as well as the restricted ductility of adhesive bonds. In most cases

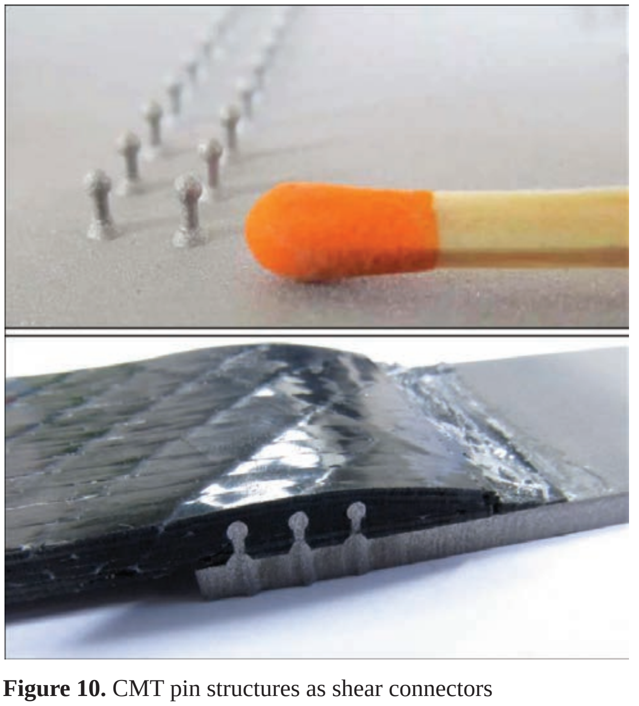

Figure 10. CMT pin structures as shear connectors

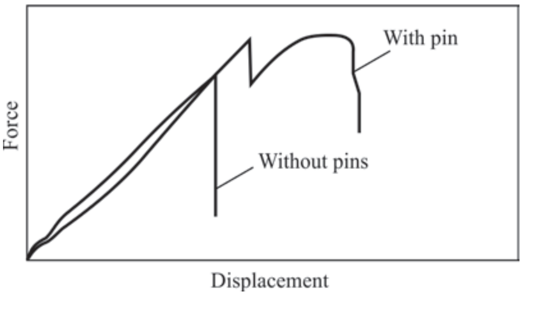

Figure 11. Multi-stage failure behavior by pin structures (schematic)

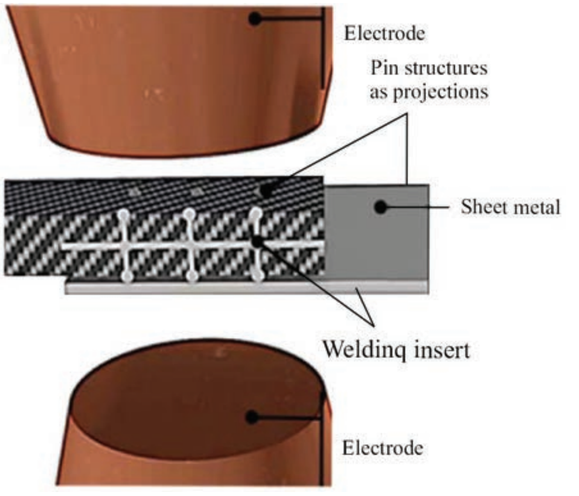

Figure 12. Welding insert for metal — FRP joints

the connections suffer brittle failure with absolutely no warning signs beforehand.

A new approach is based on an innovative, modified arc welding process where metallic pin structures are formed directly from the welding wire in one step with no additional prefabricated components needed (see Figure 10).

The pins are freely modifiable with regard to their geometry and arrangement. Therefore, they can be adjusted to the respective FRP structure.

The pin structures can be used as form-fitting elements within adhesive bonds, as has been demonstrated in the research work of the Austrian Institute of Technology in Austria. They are, moreover, suitable for moment transmission in drive shafts. Here, the drive shafts are fitted with pin structures and finally braided or wrapped with technical textiles. However, they have not yet been used to create a multistep failure behavior as it is presented in the following.

For this, the fibres are arranged around the CMT pins. The matrix resin is applied in a wet lamination process and can be directly used as an adhesive. The CMT pins transfer forces into underlying laminate layer, but also create a two-step failure behaviour:

When overloading the joint, first the adhesive bond (whose strength can be set to defined values via surface pre-treatment) fails. The forces are transported

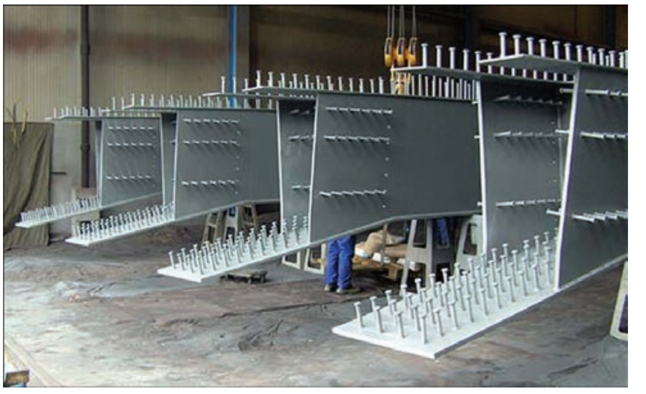

Figure 13. Shear studs in civil engineering (source: Schöler + Bolte)

via the pin structures until they also fail. This failure event can be influenced via the pins' geometry and their arrangement and/or their number (see Figure 11).

The primary failure event can be detected by an integrated monitoring system. The force level of the secondary failure event needs to be above the force level of the primary failure event for a sufficient fail-safe backup which ensures a residual load capacity for countermeasures.

A modification of the described joining process [6, 7] enables direct welding of (fibre-reinforced) plastics to metals by resistance projection welding. In this way, continuous fiber-reinforced plastics can be processed without damaging the fibers. In particular, the fabricators can continue to use existing resistance welding systems in the usual way, with minor modifications if necessary. For this, an insert is integrated locally into the (fibre-reinforced) plastic prior to lamination as part of the FRP manufacturing process. This insert consists of a carrier plate with small metallic pin structures that penetrate the fibres and the surrounding plastic, Figure 12. The insert allows current to flow through the electrically non-conductive resin and enables indirect resistance welding to metallic structures.

Steel-concrete-combinations are already known in constructions like bridges in the use of a form-fit connection by shear studs, Figure 13. However, these shear studs build an oversized connector element

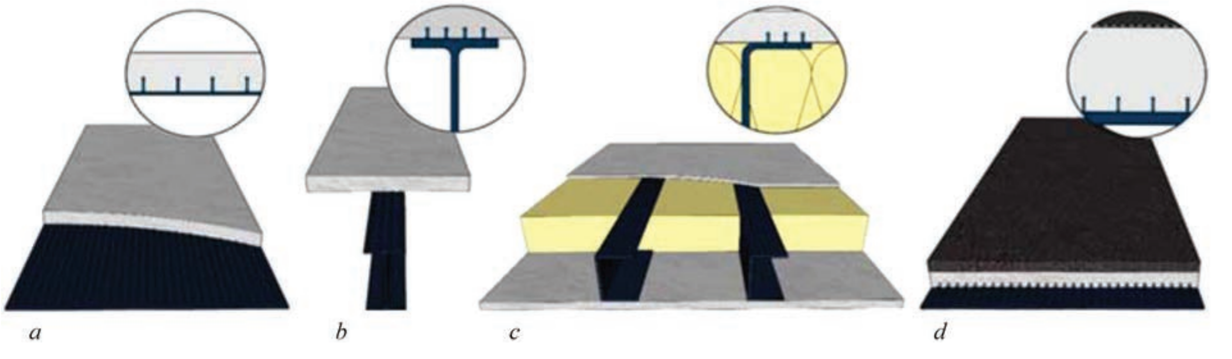

Figure 14. Applications for small-scale shear connectors

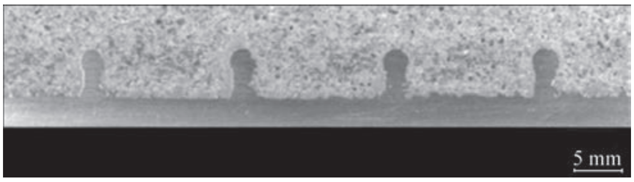

Figure 15. CMT pins embedded in concrete

for filigree designs, such as floor panels, roof girders, facade elements or bridge decks, Figure 14. The availability of small-scale connection elements such as CMT pins offers new possibilities for resource savings in lightweight constructions in civil engineering.

Strength and failure mode of the steel concrete combination vary with load and concrete type. Component tests with I-beams with concrete components on the top were performed under bending load in four point-bending tests (Figure 15).

Completely dowelled panels fail in the pressure zone of the concrete slab in the area of the load application. In contrast to this, partly dowelled panels collapse in the composite joint. The occurring failure of those panels was caused by die cutting of the concrete without a pin break (Figure 16).

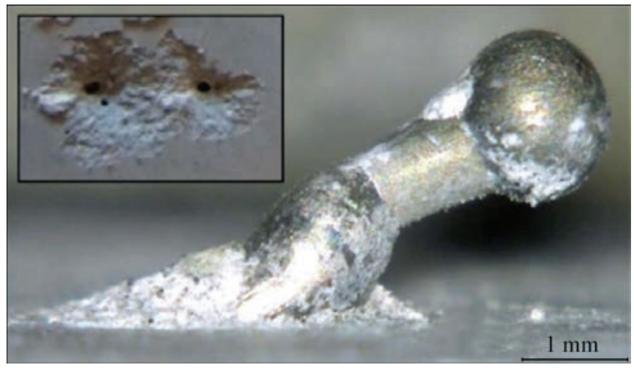

Figure 16. Die cutting failure of concrete-pin connection

Summary

Innovative new joining methods enable innovation in product design. In competition with established joining processes, they improve effectiveness or costs and open new product or production possibilities.

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Received 26.11.2018