

Innovative joining technologies for multi-material structures

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Abstract The affordable implementation of lightweight constructions in automotive engineering depends not only on the availability of suitable processing technologies for new lightweight materials but also on suitable, cost-efficient joining methods for multi-material combinations with high process reliability. Therefore, joining technology plays a key role in realizing energy-efficient vehicles. The systematic development of joining methods is necessary to overcome the metallurgical and thermal incompatibility of steel/aluminium or steel/fibre-reinforced plastic combinations. This paper presents two innovative and highly productive joining technologies and characterizes these processes based on their technological properties for one specific steel/aluminium material combination.

Keywords Joining technology · Thermal joining · Mechanical joining · Resistance spot welding · Resistance element welding · Friction element welding · Friction welding · Lightweight-design · Multi-material design · Mechanical properties · Automobile engineering · 22MnB5 · Ultra-high strength steel

1 Introduction

Despite the use of improved steel materials with better performance, vehicle weight has increased constantly with each new model generation during the second half of the last century. This was due to the introduction of technical innovations in automobile manufacturing for improving durability, driving comfort and passenger protection. Due to new environmental

laws in the European Union that force vehicle manufacturers to comply with strict limits of new cars' greenhouse gas emission, efforts in development of eco-friendly mobility must be increased significantly [1]. Besides the implementation of improved powertrain concepts, significant reductions of vehicle mass are inevitable if the challenge of reducing CO₂ emissions should be met successfully.

Intensive work on material development and advances in forming technology enable the introduction of a variety of new lightweight materials and adapted cost-efficient forming processes in automotive engineering, making it possible to reduce vehicle weight in spite of the increasing demands in the area of collision safety and comfort [2]. The following are most worth mentioning: hot forming technology for press-hardenable manganese–boron steel (e.g. 22MnB5), tailored blanks or tailored properties technologies [3], various new aluminium alloys for sheets and profiles and processes for the economical manufacturing of profile-type structures from high-strength materials, e.g. special hydroforming or roll-forming techniques [4]. Advances in manufacturing, handling and forming techniques have also led to increased interest in fibre-reinforced plastics for automotive applications. The result is a steady increase of multi-material design and technology mixtures in automotive constructions [5].

2 Requirements for joining technology

The realization of these types of car body constructions demands suitable joining technologies [6]. Conventional thermal joining processes such as resistance spot welding (RSW) quickly reach their technical limits, especially when multi-material joining is required, e.g. steel to aluminium or metals to plastics. Additionally, the use of mainly tubular components often only allows access from one side for joining purposes. Economic considerations such as the cost of investment in new machinery, expenditure for auxiliary joining parts

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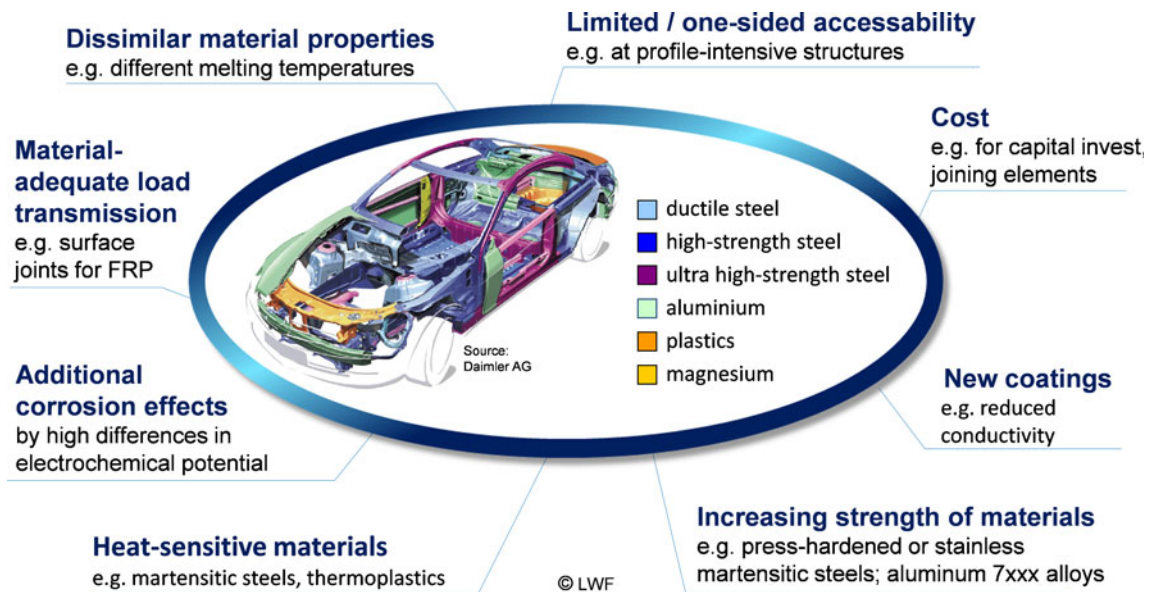


Fig. 1 Challenges in joining multi-material structures

required or process times are also important factors when choosing joining solutions. Besides, the corrosion protection of dissimilar material combinations has to be ensured. In Fig. 1, additional challenges in joining multi-material structures are shown.

To fulfil these complex requirements, a further development of technologies like adhesive bonding and mechanical or thermal joining is necessary. A promising approach for multi-material-suitable joining is an intelligent combination of more than one joining principle to a hybrid joining technology, as the following two examples show.

One present challenge for joining technology is the intensive use of ultrahigh-strength hot-stamped manganese–boron steels (UHSS) in cars for high-volume markets, which shall be combined with aluminium panels or closing plates. Due to the

high strength and low ductility of the UHSS, established mechanical joining technologies like self-pierce riveting reach their process limits.

Based on an intelligent combination of thermal and mechanical joining principles, the so-called thermal–mechanical joining technologies resistance element welding (REW) and friction element welding (FEW) were developed for joining aluminium- or fibre-reinforced plastics (FRP) with UHSS. Both require no formability of the UHSS compound [7, 8].

This paper deals with the latest results from the development of REW and FEW and compares these technologies with the established mechanical joining technology self-pierce riveting (SPR) with solid rivet regarding technological characteristics. Some aspects were already published on the German conference DVS Congress 2013 in Essen [9].

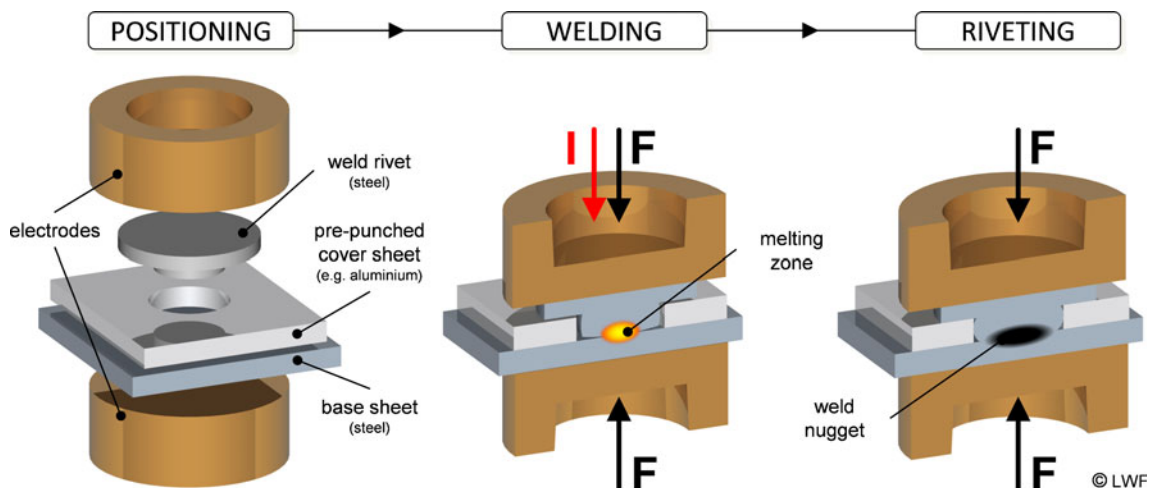


Fig. 2 Schematic illustration of resistance element welding (REW) process

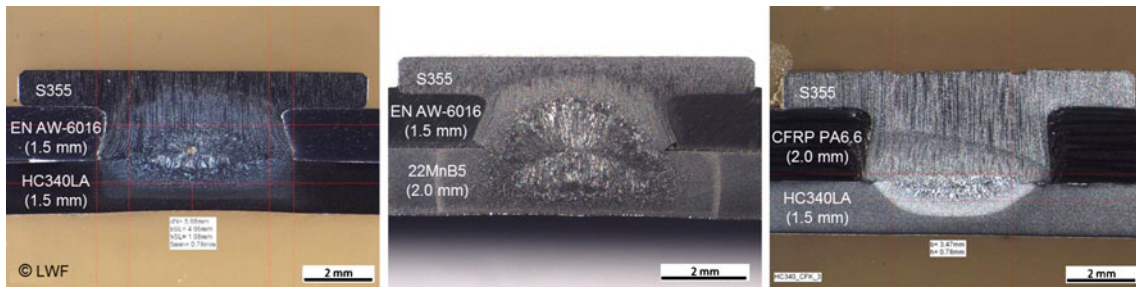


Fig. 3 Cross sections for various material combinations joined by REW

3 Resistance element welding

While conventional resistance spot welding is still one of the most frequently used joining technology in car body manufacturing, there are a number of different approaches intended to modify and adapt thermal-based joining processes in general and RSW in particular to meet the challenge of expanding the process limits to enable joining of steel and aluminium alloys. Resistance spot welding offers cost-efficiency and a high level of process reliability. Therefore, the advanced development of RSW for mixed material joining purposes promises positive results [10].

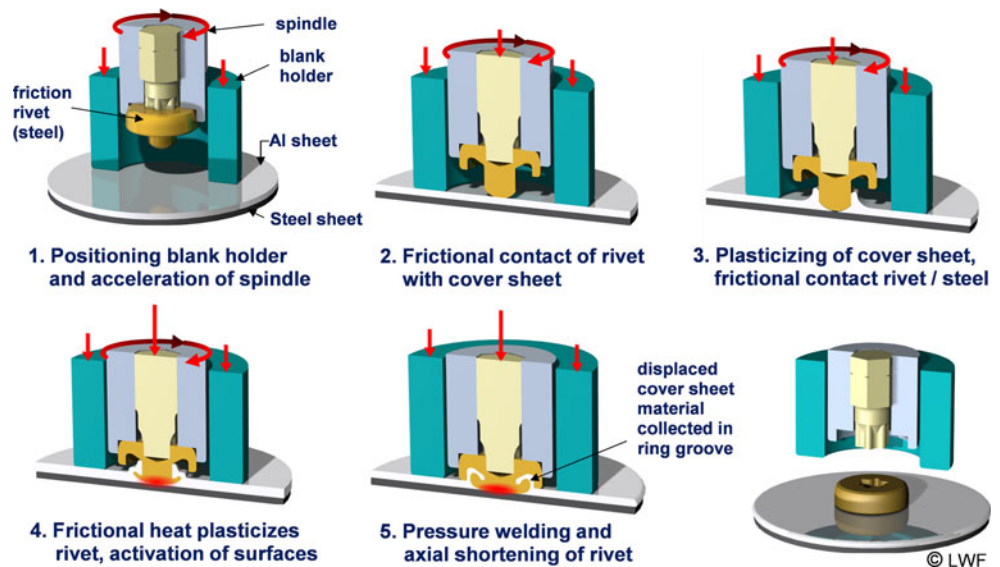
In addition to conventional resistance spot welding, the REW process is based on the use of an extra element (weld rivet) made of steel. In the first stage of the process, a hole must be inserted in the cover sheet. While simple punching is particularly suitable for aluminium, the same method can cause damage to the structure of an FRP (e.g. delamination). Therefore, alternative possibilities may be utilized, such as circular milling—which has its own particular advantages and disadvantages [11, 12]. A possible alternative is to integrate the punching operation in the welding process by selecting suitable welding rivet geometry. Another possibility is to pre-emboss the welding rivet in the cover sheet as a separate

operation, e.g. during the part stamping or forming process, which requires the cover sheet material to be ductile.

Following pre-punching, the weld rivet is inserted or positioned in the hole. Then, one electrode is lowered onto the rivet and the other onto the base sheet, and then pressure and electric current are applied simultaneously. Heat, generated by electrical resistance, causes a weld nugget formation in the contact zone between weld rivet and base sheet. An increase in electrode force leads to a weld rivet compression in axial direction and therefore to a tight force connection (surface pressure) between rivet head and cover sheet. Frictional connection occurs at the contact points between rivet shank and cover sheet (bearing stress) and between rivet head and cover sheet (surface pressure). The individual process stages can be controlled by a variation of parameter settings, generally used in resistance spot welding. For instance, weld rivet deformation can be influenced by post-heating during follow-up pressing. The process is shown in Fig. 2.

Beside the joinability of UHSS steel compounds with low ductility, the main benefit is the possibility to join both steel-to-steel material combinations (conv. RSW) and dissimilar material combinations (REW) with same resistance spot welding equipment, and thus, the process provides significant cost benefits and savings regarding equipment investment.

Fig. 4 Schematic illustration of the friction element welding FEW process



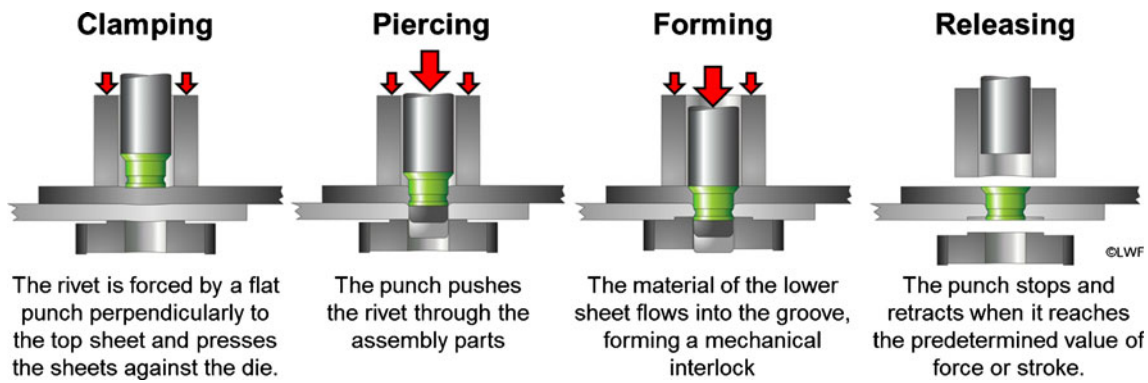


Fig. 5 Schematic illustration of SPR with solid rivet process [15]

In the course of the research project FOSTA P862 [13], REW is developed for the joining of dissimilar materials, whereby there is systematic examination of the influence of various boundary conditions. An initial influence analysis serves to determine the boundary conditions for the formation of an optimum joint and taking the demands made on conventional resistance welding joints into consideration to define suitable process parameters. In addition, the geometry of the welding rivet was optimized, for example by varying the rivet tip as well as the rivet head. At the same time, manufacturing boundary conditions such as the diameter of the pre-punched hole and the thickness and material of the cover sheet were also examined. As an example, Fig. 3 shows various cross sections for different material combinations joined with REW.

4 Friction element welding

It can be assumed that tensile strength and hardness of steels for automobile manufacturing will steadily increase. The FEW process represents an excellent alternative to other methods for joining dissimilar materials with UHSS and future new high-strength steels, e.g. TWIP steels. FEW, like REW, combines mechanical and thermal joining processes and is particularly suitable for multi-material joints consisting of aluminium and UHSS. Depending on the materials, the joint can be made without pre-punching of the cover sheet. While at conventional friction welding the components being joined may move relative to each other during the joining process, here, an auxiliary joining part is used to connect the

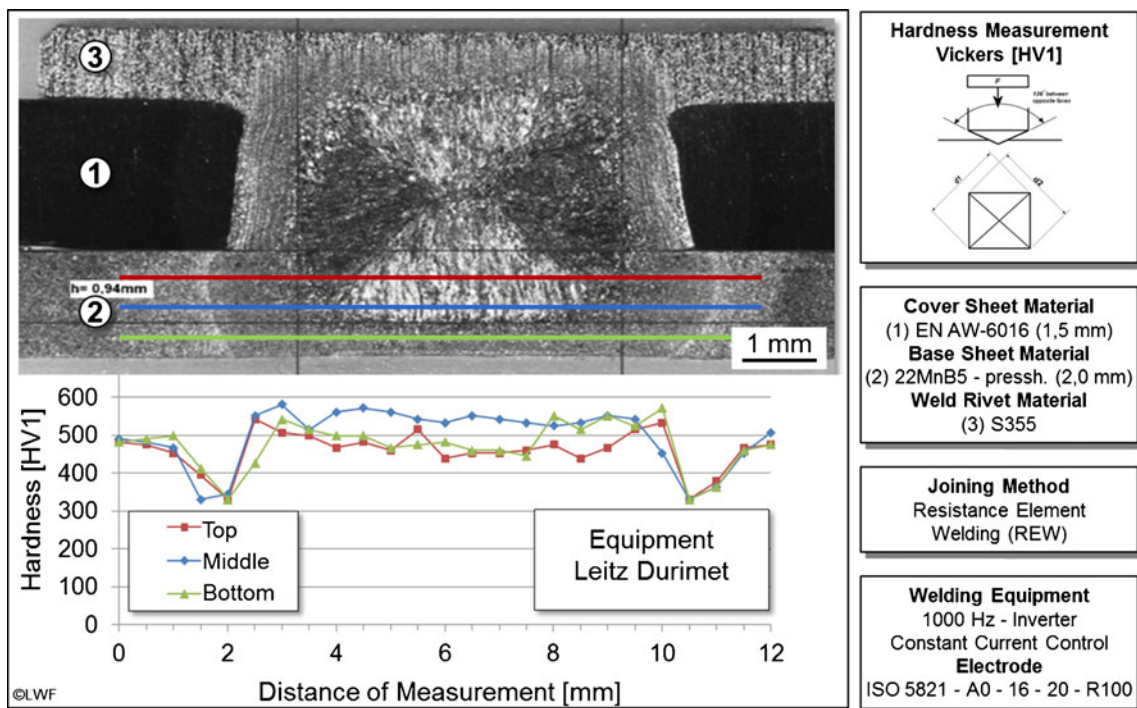


Fig. 6 Cross section and hardness profile of REW joint

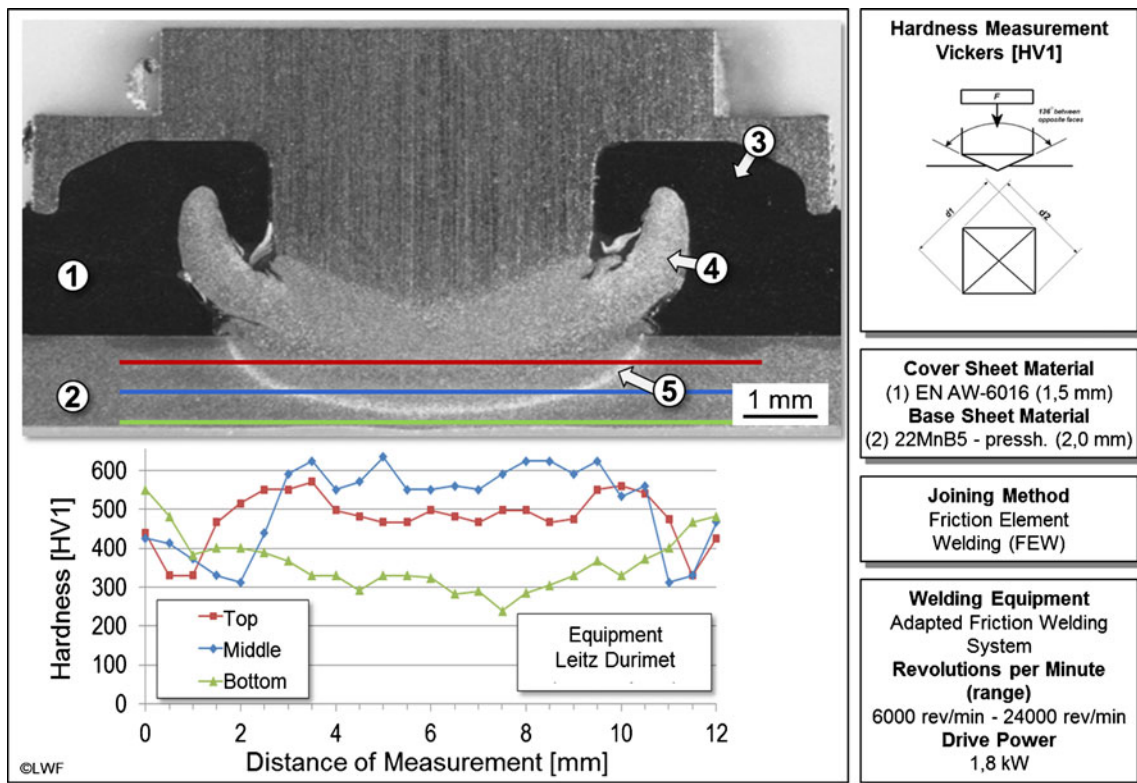


Fig. 7 Cross section and hardness profile of FEW joint

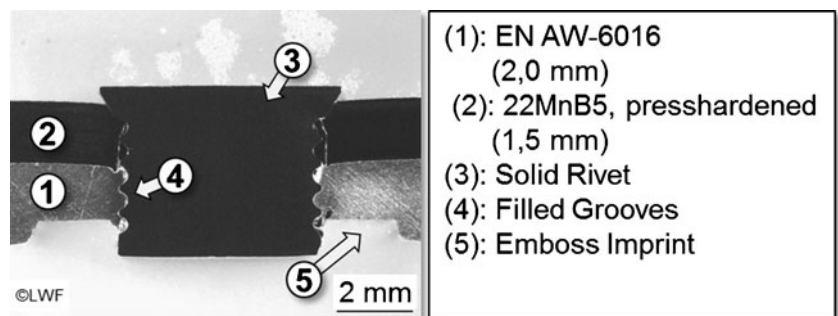
components. The process principle of the FEW process without pre-hole is shown in Fig. 4.

In the initial step, the two parts to be joined are secured with a blank holder to prevent gaps between the parts. Then a rotationally symmetrical element revolving at high speed is placed on the cover sheet at high pressure. The resulting frictional heat plasticises the cover sheet material without being melted, allowing to penetrate the top layer sheet by the friction element. The geometry of the friction element tip causes the plasticised material to be transported out of the joining zone and displace the surrounding material, which can be collected by a groove under the element head. The friction phase that generally takes up the most part of the process time begins with the contact of the rivet and the lower UHSS sheet. The combination of frictional heat generated between the friction element and the steel sheet surface and the high axial

forces cause the formation of characteristic welding beads around the friction element, accompanied by a shortening of the element. After a certain shorting or energy input, the spindle can be decelerated to a standstill, and the compression phase with increasing axial force produces the friction pressure welding effect. The friction element is slightly shortened again, resulting not only in a strong steel-to-steel bond between friction element and base sheet material, but also a positive form fit with the cover sheet [14].

A wide range of applications and improved joining properties can be achieved by adapting element geometry and process parameters. If the cover sheet material is sufficiently ductile, the process does not require pre-punched holes, which in turn reduces costs for pre-punching or the time-consuming positioning of joint elements before the joining process. In cases of a friction-resistant cover sheet material, nevertheless,

Fig. 8 Cross section of SPR joint



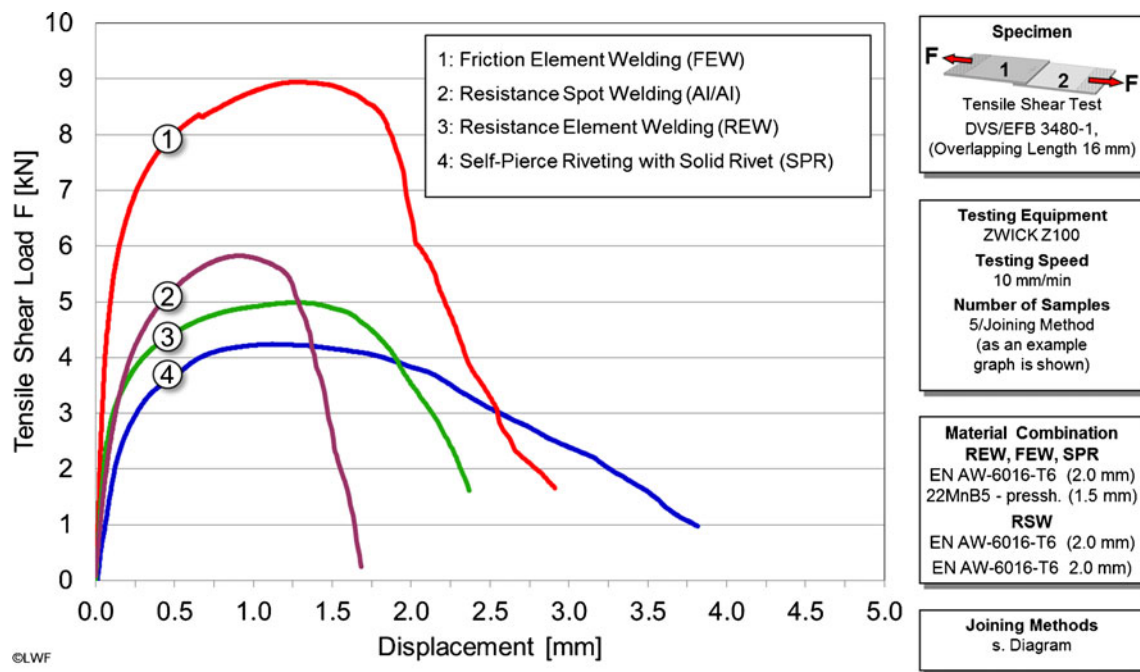


Fig. 9 Force-displacement behaviour of considered joining methods in comparison to RSW of Al/Al joints

the process can be used if a hole is pre-punched and the friction element adapted [14]. The process offers additional significant advantages. Unlike REW, the FEW process generates relatively low process temperatures in the joint area and does not cause material melting, so temperature-sensitive materials can also be joined.

5 Self-pierce riveting with solid rivet

SPR with solid rivet, shown in Fig. 5, is a mechanical cold joining process to fasten two or more sheets of material by pushing a rivet through the stack from one side without the need to drill or punch a hole. SPR is already in use for high-volume production of car body structures.

After clamping the sheets to be joined by a blank holder, the punch pierces the rivet in the sheets with the less ductile properties (e.g. 22MnB5) at the top. In order to create an interlock, the process force is increased to initiate a plastic deformation of the die-sided sheet, forcing the material to fill

the groove of the rivet. In order to avoid deformation during punching, the so-called emboss ring must be adapted to the required punching forces, depending on the material combination. The result is a force and positive lock.

SPR with solid rivets enables joining of multi-material and multi-layer combinations. Depending on the application, different rivet geometries and rivet materials as well as rivet coatings are used. A high flexibility can be realized by using multi-range rivets with additional grooves allowing to join different material thicknesses [15].

6 Experimental results

All proposed joining technologies provide high application potential for joining press-hardened manganese–boron steels with aluminium and are also under investigation at German car manufacturers [e.g. 16, 17]. In the following, selected results are shown regarding hardness profiles and the strength properties with and without additional adhesive bonding

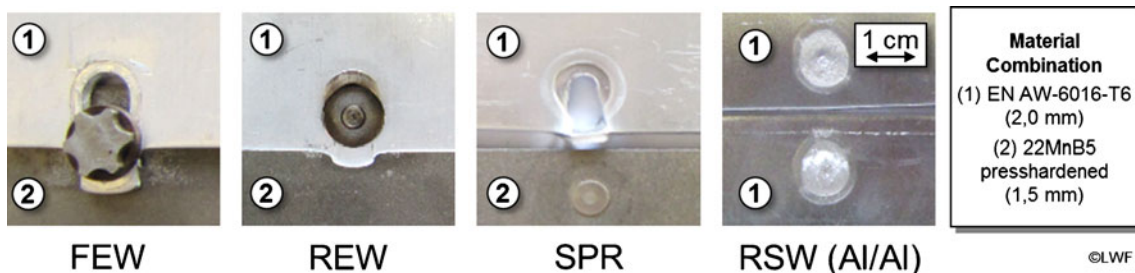


Fig. 10 Occurring failure modes by tensile shear load

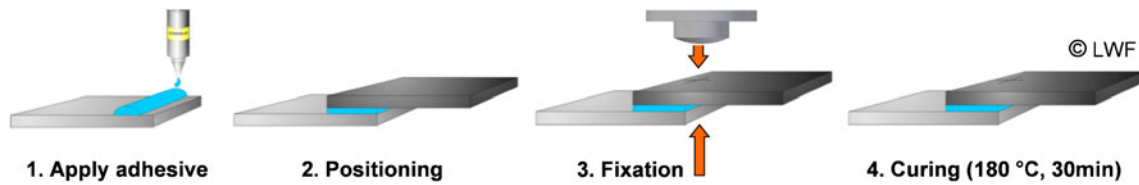


Fig. 11 Schematic illustration of adhesive application

(hybrid joining). A variety of different materials was used in order to generate high-significance test results for future automobile trends. In particular, a press-hardened steel 22MnB5 (1.5528) with a thickness of 2.0 mm and no coating was chosen as base sheet. The material used for the cover sheet is an automotive-typical 6000 series aluminium alloy (EN AW-6016, AlMg0,4Si1,2).

6.1 Joint properties

Figure 6 shows a cross section and the hardness profile within the weld nugget and the heat-affected zone (HAZ) for the considered material compound joined by REW. A medium-frequency (MF-DC) resistance spot welding system with conventional electrodes (ISO 5821-A0-16–20-R100) was used.

During the resistance welding process, melting of the martensitic manganese–boron base sheet material and the weld rivet material occurs. This results in local hardness decrease in the HAZ and hardening increases in the solidification range of the weld nugget. Figure 7 shows a cross section and the hardness profile within the weld of a joint made by FEW. The process was performed with an adapted friction welding equipment at a speed of 18,000 rpm and pneumatically generated axial force.

The essential characteristics consist of the formation of welding beads around the friction element (4) and the weld zone with the HAZ (5). Compared to the REW process, the temperature during the FEW process in the joining zone is lower. Therefore, melting temperatures of the steel compounds are not reached, and a weld nugget formation does not occur. The aluminium material is displaced by the penetration of the friction element shank and the bead. This plasticised aluminium material is collected under the friction element head in the circumferential groove without the occurrence of any pores or cracks (3). This results in a locally higher thickness (approx. 3.25 mm) of the aluminium sheet which leads to higher maximum forces when testing under tensile shear load. Despite the low heat generation during the friction welding process, significant changes in structure and hardness profile in the HAZ can be observed. While at the base sheet bottom annealing effects lead to a slight decrease in hardness, the increase in the diffusion-welding zone is significant. By varying the process parameters (axial and rotational speed in the different phases of the process), the shape of the bead as well as the shape of the HAZ can be influenced.

Figure 8 shows a cross section of a compound joined by SPR with solid rivets. A multi-range solid rivet made of 1.4035 material was used. The maximum process force was

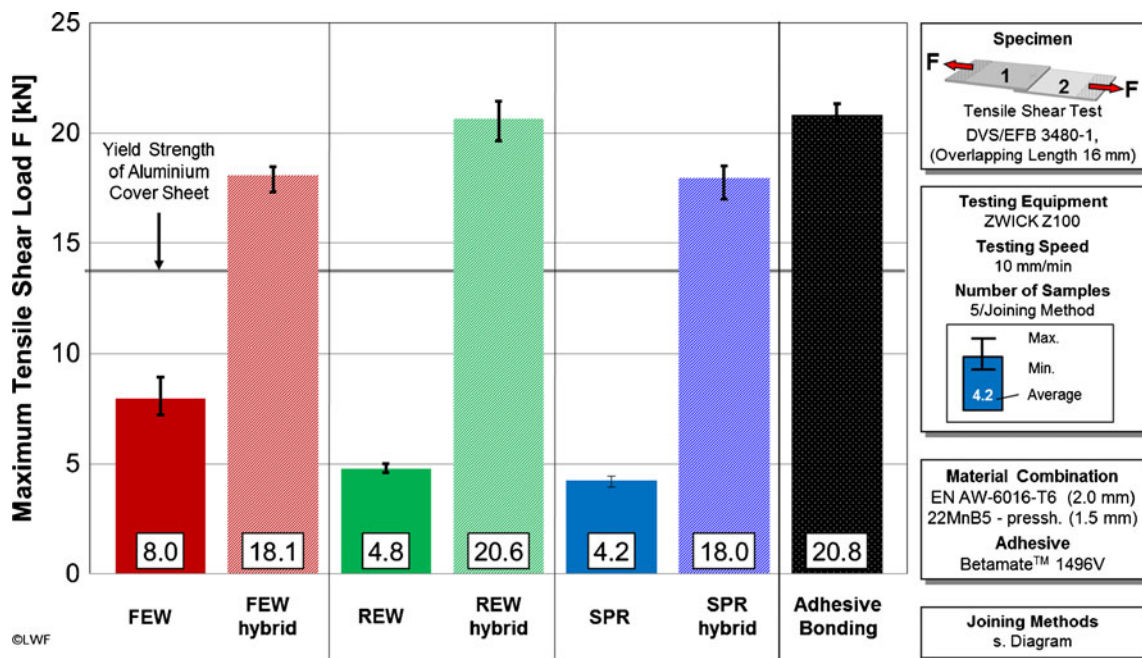


Fig. 12 Comparison of maximum tensile shear loads of considered joining methods in combination with adhesive bonding (hybrid joining)

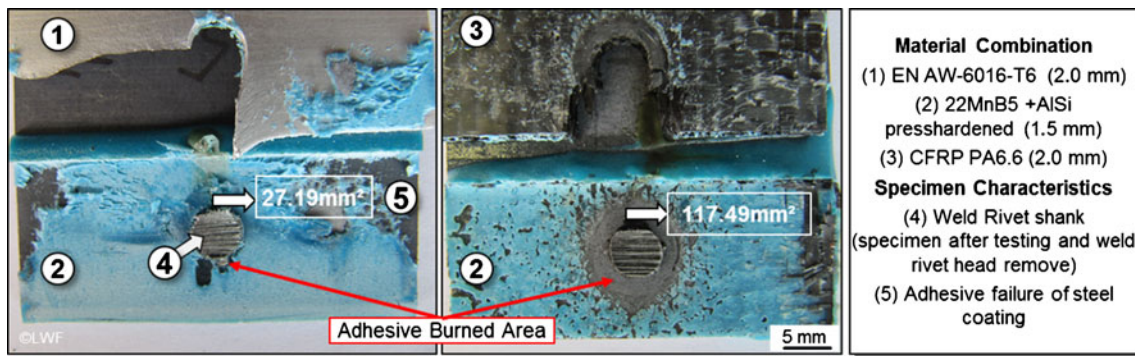


Fig. 13 Comparison of adhesive burnt area sizes of different material combinations for REW-hybrid joining process

41 kN. The aluminium base sheet material fills in the grooves on the rivet perimeter and leads to an interlock of the parts.

6.2 Strength comparison—tensile shear test

In this section, a comparison of selected mechanical properties of joints, made by REW and FEW of the dissimilar material combination EN AW-6016 and 22MnB5 (press hardened, no coating), is given. In order to classify the mechanical properties by comparing them with other joining methods, SPR with solid rivets was chosen. The most important mechanical property of joints is the behaviour by quasi-static load application. In this section, the tensile shear test was selected. The strength examinations were performed according to German standard DVS/EFB 3480-1 (shear testing with specimen overlapping length of 16 mm) [18]. The force-displacement behaviour is shown in Fig. 9. For comparison reasons, a batch of five

resistance spot-welded aluminium/aluminium joints was selected.

The FEW joints failed within a range of approx. 7.2–9.0 kN compared to the average maximum load of approx. 5.8 kN of Al/Al spot-welded joints, 4.5–5.0 kN of REW joints and 3.9–4.4 kN of SPR joints. The high load bearing capacity of FEW joints is generated by the local thickness increase under the rivet head, which forms an additional shear plane. Furthermore, the variations of the strength properties of REW, FEW and SPR occur due to different shank and head diameters of the inserted rivets and therefore different load bearing capacities. The occurring failure modes are shown in Fig. 10. While the primary failure mode of REW and FEW joined specimens is bearing deformation of the cover sheet, the self-pierce riveted joints fail after a deformation of the Al sheet by tearing out the rivet of the Al sheet. Thus, the rivets and the weld zone for both the REW and the FEW remain

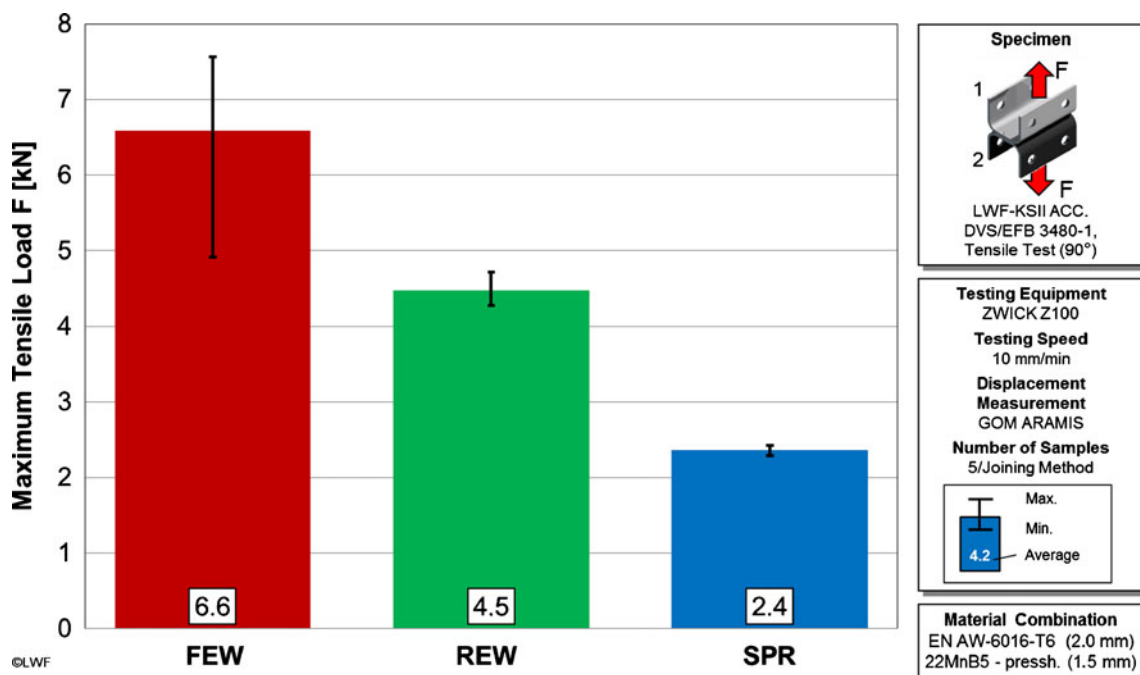
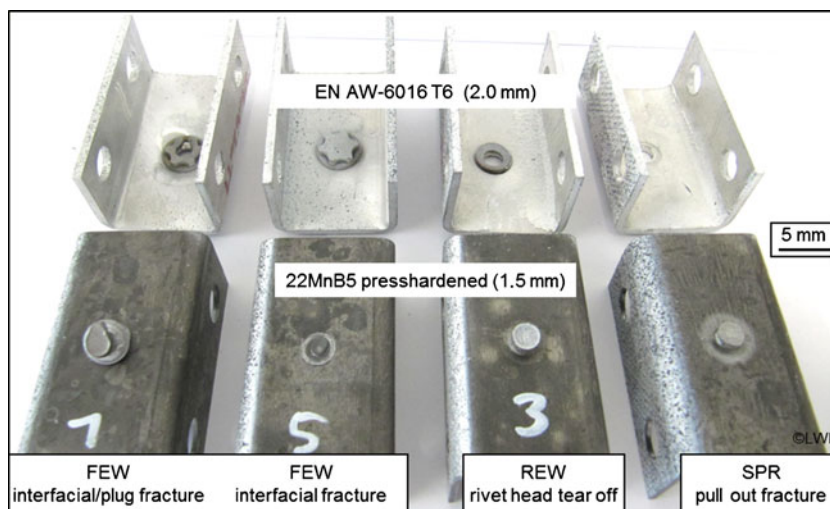


Fig. 14 Comparison of maximum tensile loads for FEW, REW and SPR joints

Fig. 15 Occurring failure modes for FEW, REW and SPR joints



intact. The failure mode of all joints (except RSW) shows that the average maximum joint strength is mainly determined by the strength of the cover sheet material.

6.3 Strength comparison—hybrid joining

In today’s car body construction, adhesive bonding is combined with different point joining methods. The advantage of adhesives is a continuous joining with good stiffness and fatigue resistance. A continuous bondline has the additional benefit of reducing noise vibration and harshness. Besides being required to fix and hold parts together, the main drawback is a low mechanical strength in peel loading situations. The combination of adhesive bonding with point joining methods can compensate the low peel loading strength by acting as a peel stopper; it also aids a more rapid assembly by putting parts together prior to the curing process of the adhesive in the paint bake cycle [19].

The combination of REW, FEW and SPR with adhesive bonding is known as hybrid joining. Various methods of applying the adhesive exist, whereby the fixation process is most suitable. The basic principle is shown in Fig. 11.

For determination of joint properties of REW, FEW and SPR in combination with adhesive bonding, the one-component epoxy-based adhesive Dow Betamate™ 1496V was used. As the automotive industry tends to favour simple low-cost surface treatment, any contamination was removed and the surface degreased using acetone and isopropanol prior to adhesive application. The adhesive layer thickness was set to 0.25–0.4 mm. The manufactured specimens were cured by heat treatment for 30 min at 180 °C, simulating the typical automotive paint bake process after cataphoresis painting. With samples prepared this way, different strength analysis focusing on various material combinations, overlapping lengths, etc., were carried out. As an example, Fig. 12 shows the force-displacement behaviour of EN AW-6016-T6

aluminium joined to 22MnB5 steel for hybrid and elementary joints by tensile shear load application.

The figure indicates a high potential in strength increase by combination of REW, FEW and SPR with adhesive bonding. The average maximum loads are much higher than the yield strength (approx. 13,75 kN) of the aluminium cover sheet material in T6 tempered condition. Hybrid joining therefore allows a high utilization of the used materials, which is essential for lightweight design attempts. The tensile shear strength of REW-hybrid joints is increased significantly and also higher than the strength of FEW- and SPR-hybrid joints. The reason is a bigger effective adhesive layer area. While the generation of heat flow during the REW process burnt off the surrounding adhesive only within a small area (Fig. 13), the FEW and SPR processes squeeze the uncured adhesives from in between the sheets and reduce the effective adhesive

Table 1 Comparison of characteristic properties of REW, FEW and SPR joining methods

Evaluation criteria	REW	FEW	SPR
Joining dissimilar materials	+	+	+
Material flexibility (steel–steel, steel–Al, FRP–metal)	+	~	+
Hybrid joining (combination with adhesive bonding)	+	+	+
Joining press-hardened steel w/o pre-hole	+	+	+
One-side accessibility	+	~	–
Low compound deformation	+	+	~
Surface flatness	~	~	+
Simplicity of process	~	~	+
Good reproducibility	+	+	+
Low joining/setting forces	+	+	–
Process time (only joint setting)	+	~	+
Low workplace and environmental pollution	~	+	+

+ positive, ~ fair, – negative

layer area significantly. Due to its high setting forces, the SPR process particularly enhances that negative effect [20].

In resistance welding-based processes, such as REW, the heat generation leads to damage of the adhesive in a certain radius around the joining point. For REW, besides the choice of the optimal welding parameters, the cover sheet material and its thermal conductivity have a large influence on the adhesive damage. By contact of the weld rivet with the aluminium cover sheet, a part of the introduced heat is removed evenly while the use of FRP as cover sheet material leads to heat accumulation and much bigger adhesive burnt area size. The total adhesive area reduction of the steel/aluminium combination is only 27.19 mm², while the reduced adhesive area for steel/CFRP is much bigger (117.49 mm²). For steel/aluminium combinations, this results in strength properties comparable to the solely bonded joints with fully sized adhesive layer area. In addition, the comparatively large rivet head increase the local specimen stiffness and contributes as a peel stopper by reducing the bending moment during tensile shear test.

6.4 Strength comparison—tensile test

For an examination of the absolute tensile strength, the specimen deformation and bending moment occurrence of the aluminium cover sheet material must be excluded, and therefore, an adjustment of the specimen concept is necessary. For this purpose, a patented rigid LWF KS-II specimen geometry was chosen for testing under tensile loads. The maximum tensile loads of joints with this specimen geometry are illustrated in Fig. 14.

The FEW joints break at an average maximum tensile load of 6.6 kN compared to 4.5 kN of the REW joints and 2.4 kN of the SPR joints, respectively. Due to the big head of the auxiliary joining element of the FEW, the maximum tensile load is much higher. The variation occurs within a bigger range due to different failure modes. While a set of specimens shows a combination of interfacial/plug fracture, another set of specimens shows a full-interfacial fracture in the weld zone. Further optimization potential of process parameters and element geometry is required. The REW failure mode is based on a rivet head deformation and a final tear off. The SPR joint failure mode is pull out off the aluminium sheet (Fig. 15).

7 Conclusions

Joining technologies are essential for the realization of innovative and energy-efficient lightweight construction for combining dissimilar materials in multi-material design applications. Ever-increasing material diversity, particularly in automotive body construction, as well as demand for process reliability, availability, flexibility and cost-efficiency results

in a high level of innovation pressure in the field of joining technology. This paper presented current developments and processes based on the state of research at the Laboratory of Materials and Joining Technology. A comparison of the characteristics of the considered variants of the REW, FEW and SPR process is given in Table 1.

REW and FEW combine mechanical and thermal joining principles, a combination that offers a number of advantages comparing to processes that are purely thermal (limited metallurgical feasibility of multi-material joints) or purely mechanical (restrictions regarding formability of at least one of the joining parts). Due to low process forces, REW and FEW offer high potential for profile-intensive constructions, being suitable in cases where access to the joint is limited to one side only. The process time of FEW is about 1.7 s and is thus a bit longer than REW and SPR. The advantage of SPR with solid rivet is the simplicity of the process (e.g. less process parameters) and the higher material and sheet thickness flexibility.

The continuous development and qualification of these and other joining processes within the framework of cooperative industrial research and other publicly funded support programmes represent an important contribution to the realization of future lightweight and eco-friendly mobility. At the Laboratory of Materials and Joining Technology (LWF) at the University of Paderborn, successful innovative joining technologies are developed since 1976.

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