Hybrid technologies for joining ultra-high-strength boron steels with aluminum alloys for lightweight car body structures

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Abstract

Lightweight design in car body engineering enables the reduction of energy consumption and greenhouse gas emissions of cars, which is crucial to fulfill the increasing legislative restrictions and market demand for eco-friendly mobility. The challenge is to realize more lightweight and at the same time still rigid and crash-stable car bodies, that are affordable for a large-scale production. For cars for high volume markets, an intelligent load-oriented multi-material design with intensive use of ultra-high-strength hot-stamped boron steels combined with modern aluminum alloy sheets and cast is often the optimal solution, as these materials offer a great weight reduction potential at reasonable costs. The lack of suitable cost-efficient joining technologies for these material combinations is one of the most important barriers for the realization of affordable cars in volume productions. This paper presents and overview about recent developments and research results for suitable joining technologies.

Keywords: Multi-material design, lightWeight design, joining technologies, boron steels

1. Introduction

In recent years, the European automotive industry is focusing on the development and implementation of innovative technologies to reduce fuel or electric energy consumption of cars, e.g. by lightweight design. Measures often focus on the implementation of various lightweight materials like advanced high-strength steels, aluminum or magnesium alloys and fiber-reinforced plasctics into the car body structure. Driven by the diverse and locally different requirements on a car body structure, multi-material design is the most common approach to weight reduction in the car body among car manufactures [1]. Not all of the mentioned materials are yet affordable for a large-scale production.

For cars for high volume markets, an intelligent load-oriented multi-material design with intensive use of ultra-high-strength hot-stamped boron steels (UHSS) with tensile strengths up to 1,650 MPa in structural parts combined with aluminum alloy sheets as skin or floor panels is often the optimal solution, as these materials offer a great weight reduction potential at reasonable costs. [2]

Due to the reduced solubility of Fe in Al at room temperature and the resulting formation of brittle intermetallic phases, standard automotive welding processes such as resistance spot welding are not applicable in series production environment [3]. Developments for a controlled formation of the intermetallic layer size by controlled heat input are not applicable in series production environment, when it comes to join boron steels with the typical Al-Si-coating [2].

Therefore, the focus is on adhesive bonding, combined with mechanical joining technologies. Established mechanical joining processes suitable for multi-material joints like self-pierce riveting (SPR) or clinching can reach their process limits due to the high strength and low ductility of UHSS. [4]

This requires further improvement of existing mechanical joining technologies or the development of new suitable...
methods with high productivity. High productivity especially includes short process times, none or inexpensive auxiliary joining elements as well as fast and simple positioning of the joining equipment. A prerequisite for fast positioning is that the parts to be joined require no previously punched or cut holes in the parts for the joining process. [2]

This paper presents four innovative productive methods for joining boron steel parts with aluminum sheet.

2. Introduction of innovative joining technologies

2.1. Self-pierce riveting with solid high-strength rivets

Self-pierce riveting with solid rivets allows joining punch-sided high-strength materials with die-sided ductile materials. Fig. 1 shows a process illustration. After a fixation of the parts to be joined by the blank holder, both parts are punched by the rivet. The following increase of the process force results in a penetration of the die-sided material by the emboss ring of the die. The die-sided material is plastically deformed and partially flows into the circumferential groove of the rivet, whereby a positive lock is formed (see image 3 in Fig. 1).

In contrast to classic self-pierce riveting with semi-hollow rivets (see Fig. 2), the process does not require to form the rivet plastically to create a positive lock. This allows utilizing rivet materials with very high tensile strengths and high hardness, which enable a process-capable punching of boron steels with the solid rivet. However, this requires relatively high process forces for punching the parts to be joined and forming the interlock.

As already described above, it is mandatory to use adhesive together with a mechanical joining technology in order to exploit the lightweight potential of the materials. Due to the high process forces of the SSPR process and the forming of the interlock by a relatively large plastic deformation of the die-sided material, adhesive is squeezed out of the joining zone, resulting in locally different adhesive layer thickness. In addition, spring-back effects of the die-sided sheet can occur, when the joint is released from the joining equipment during return stroke (see Fig. 2, left image). This spring-back results in gaps in the adhesive layer. These effects drastically decrease the strength of the hybrid joint due to a reduction of the effective adhesive area. Furthermore the vulnerability of the joint against corrosive media increases, due to less isolation of the materials by the gaps in the adhesive layer. Several recent research projects performed by the LWF focussed on the optimization of the hybrid joint. The development of a new rivet geometry in combination with a modification of the setting tools (blank holder and die) lead to a large improvement of the quality of the adhesive layer and therewith to significantly higher strengths of the hybrid joints, see Fig. 2. The developments also work for multi-layer joints with boron steels. [5]

2.2. Local conditioning of the joining zone

Established and mature joining processes such as self-pierce riveting with semi-hollow rivets (SPR) or classic non-cutting clinching processes fail to join boron steel in fully martensitic condition due to its brittleness, high tensile strength and hardness.

For typical boron steel parts, such as b-pillars or rockers, are already several technologies available, which enable to realize in the same part areas with different mechanical properties (soft/hard) for an improvement of the crash performance of the part. This is done by a modified heat treatment during or after the hot-stamping of the boron steels, resulting in different metallic structures with different mechanical properties.

This principle can be transferred to the requirements of established mechanical joining technologies. The so-called local conditioning is a separate process step after hot-stamping. It was developed in a recent public-funded research project [6]. During the process, a short-cycle heat treatment, e.g. by robot-based induction or laser equipment, is applied locally limited to the areas, where mechanical joining is necessary in the subsequent assembly process. The controlled energy input allows various temperature profiles and therewith to transform the martensitic structure partially or fully into annealed martensite, bainite or ferrite-perlit. [2; 6] This permanently transformation is only locally, while the global part properties are not affected. The mechanical properties of the joining zone can be adjusted to the specific requirements of the various mechanical joining technologies.
in the desired way. This technology extends the application limits of established productive joining methods to ultra-high strength steels.

As an example, Fig. 3 shows the decrease of Vickers hardness in the conditioned zone for two different temperature-time-treatments. By a short-cycle annealing at 700 °C for 4 seconds, hardness and tensile strength is already reduced to approx. 280 HV30, what is sufficient for joining punch-sided boron steel parts with a conventional self-pierce rivet [2; 6].

With a more complex and longer temperature profile including a short austenitization phase, martensite is transformed to ferrite-perlite and bainite. Therewith, ductility is increased significantly, allowing to join the boron steel part even die-sided with a conventional self-piercing rivet (see Fig. 4).

Fig. 3: Measurement results of Vickers hardness in boron steel part before and after local conditioning with different cycle times.

Fig. 4: Left: Cross-sections of SPR joint without conditioning showing cracks in the die-sided boron steel part due to its low ductility. Right: Cross-section of SPR joint with locally conditioned boron steel part.

2.3. Development of the shear clinching process

The conventional clinching process is limited by the tensile strength and ductility of the joining materials [7; 8]. Recent studies investigated the possibility to join aluminum alloys with high-strength steel up to 980 MPa tensile strength using adapted dies for the control of the metal flow [9], but yet there are no reliable engineering solutions known for conventional clinching of ultra-high-strength boron steels. A well-known solution for clinching aluminum alloy with boron steel is the use of a pre-punched hole in the steel part. However, the exact positioning of the joining equipment to the pre-hole under series production conditions is difficult and results in poor cycle times.

In contrast to that, the innovative shear-clinching process does not require pre-punched holes and expands the application limit of clinching to boron steels and other hard-to-form materials. The fundamental idea of shear-clinching is a single-stage process in which a punching of the die-sided boron steel material is performed by indirect shear-cutting and subsequent forming of the upper layer into this hole, see Fig. 5.

Fig. 5: Shear-clinching combines a shear cutting of the high-strength steel part with a clinching process with pilot hole in one process.

The use of a punch set consisting of outer and inner punch realizes the indirect shear-cutting operation of the die-sided material. During the process, a fixed anvil causes the radial material flow of the punch side ductile material. The lateral extrusion process is controlled by the opening of the die lamellae and the resulting interlock between the joined materials creates a form-fitting, non-positive connection.

This process is currently under development. According to recent investigations [10] the strength of the joints greatly depends on the thickness of the punch-sided material. A higher strength of the die-sided material supports the punching process during the clinching sequence. These results give a good orientation for the material combination of further studies like the development of a processing window and the optimization of the tool geometries.

Fig. 6: current investigation in “Mechanical joining of dissimilar materials by shear clinching processes without pre-punching (shear clinching)” by LFT and LWF [11]

First results show the joinability of aluminum in 2.0 mm and hot-stamped 22MnB5 in 1.5 mm, see Fig. 6 [11]. Average joining forces at maximum come to 90 kN. At the moment there are no guidelines or process windows available. For that reason, investigations of the process parameters like
modifying the punch geometry (angle, chamfer) are necessary.

2.4. Thermal-mechanical joining processes

To avoid the occurring high process forces when piercing or forming the brittle and hard boron steel during a mechanical joining process, mechanical joining principles were combined intelligently with thermal joining principles to new joining methods. The so-called thermal-mechanical joining processes like resistance element welding (REW) use an auxiliary joining element made of steel (weld rivet), which is joined by a welding process with the boron steel part, while the aluminum sheet is joined with a positive and a force lock to the auxiliary element. The use of an auxiliary weld rivet allows creating a strong metallic fusion to the boron steel part without the formation of intermetallic phases. [4, 12]

REW requires a separate process step before joining. The weld rivet is pierced with a form fit into the aluminum sheet part during or after the aluminum part stamping process (see Fig. 7). Conventional spot welding equipment can be used for welding the rivet to the boron part in subsequent assembly processes. [4]

![Fig. 7: Illustration of resistance element welding process][2]

3. Comparison of joint performance under shear load

Besides the development and improvement of the processes, investigations on process stability and the identification of suitable process parameters, destructive testing of joints is mandatory to analyze the load bearing capability and failure modes. In the context of this paper, selected test results from quasi-static lap-shear tests are presented.

The specimens had an overlapping length of 16 mm, according to typical automotive flanges and according to German guideline DVS/EFB 3480-1 [13]. Five specimens per joining method were tested under tensile shear load at a speed of 10 mm per minute. From the results displayed in Fig. 8 can be observed, that the standard deviation of the maximum forces of each joining method is relatively low, showing a good reproducibility of the developed joining processes. The table also proves that the maximum process forces can be increased significantly by using epoxy-based heat curing structural adhesive. During testing of hybrid joined specimen, the aluminum parts are plastically deformed. It can be concluded, that the hybrid joints are able to transmit high loads with a high utilization of the material, what is an important aspect for lightweight design [2]. The displayed results prove that the above presented approaches for joining boron steels with aluminum alloy sheet are able to realize adequate joint performances. Due to the different joining principles applied to the multi-material joint, the required average process forces vary from only 6.0 kN for resistance element welding to 87.5 kN at shear clinching (Tab. 1).

![Fig. 8: Comparison of mean maximum forces and standard deviations under shear load of joints made of AA6016 and 22MnB5, produced with the presented joining methods with and without additional adhesive bonding (SSPR = Self-pierce riveting with solid rivet; SPR = Self-pierce riveting with semi-hollow rivet; SCL = Shear clinching; REW = Resistance element welding)][6; 12]

![Tab. 1: Comparison of mean maximum process forces for joints made of AA6016 and 22MnB5.][6]

4. Conclusions

The presented technologies are highly suitable for joining of high-strength steels with aluminum alloys and other non-ferrous materials in automobile car body production. Self-pierce riveting with solid rivet and shear-clinching do not require any previous preparation of the parts such as conditioning or insertion of a weld rivet, but require relatively high process forces with stiff and therewith heavy-weight C-frame-equipment, what can make a robot integration more expensive. By combining the punctual joining methods with structural adhesive bonding, the joint performance can be enhanced significantly, if the influences between the joining processes and the adhesive are considered and corresponding optimization measures are taken. [4; 14]
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