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Production of hybrid FRP / steel structures with a new sheet metal connecting element

Abstract: This article considers the technology of thermal welding of new auxiliary elements for the connection of composite materials and metal components in hybrid structures. As the basis, the iterative adjustment process of optimization penetration into the composite material with the lowest level of material damage is used. Also, in this paper, the main requirements, which appear through the process of the welding element adjustment, are considered from the welding prospective. Various concepts of elements connection will be represented and analyzed. Moreover, the achievement of low energy input in a base material in order to minimize the thermal damage of the composite materials will be showed. Therefore, new approaches in resistance spot welding are required and some of them are represented in this article. Despite the obtained welding joints, the article also represents their mechanical characteristics and welding parameters.

Keywords: FRP/steel, structures, thermal welding, composite materials joining

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Introduction

In the 90s of the first attempts to introduce a lightweight concept in the automotive industry, the reduction of fuel consumption and carbon dioxide (CO_2) emissions were implemented. [1] In order to fulfill the legal requirements for emission reduction and fuel consumption, it is necessary to make further reduction of car weight. Today, the car body is still the most massive component of the car and has great potential to be reduced. [2, 3] The trend in weight reduction led to the development and usage of high-strength steels, for instance, manganese-boron steel 22MnB5 and Multi-Material-Design with such materials as aluminum, composite materials or sandwich materials. [4, 11] Moreover, the welding joints play a key role. Classical welding technologies could not be used because of the heat input as well as the incompatibility of the welded materials. Mechanical joint methods, such as screwing, self-tapping screws or rivets, have disadvantages such as damage to the carrier fibers in the composite material. [5, 6] Thus, for the creation of the connection between high-strength steel and composite materials, resistance spot welding is used.

Resistance element welding (REW)

The resistance element welding (REW) is a joining method which allows two metallurgically

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incompatible materials to be joint. Initially, the method was invented to join aluminum with high strength steels. It is primarily used for application within the car body. The REW process is divided into two parts. In the first step, a suitable steel element for welding is mechanically stamped into the external cover plate and welded in the second step by means of resistance spot welding to a steel plate. [7] In contrast to mechanical joint methods, as riveting or clinching, REW joining does not require any ductility of the base plate.

Low-damage Penetration

For the desired compound of steel and fiber reinforced plastic (FRP) the fiber penetration of the composite coupling element must be designed in such a way that the mechanical loads would be absorbed by fibers. In the standard connection methods, such as riveting and binding, the destruction of bearing composite fibers occurs, resulting in the reduction of joint strength.

Direct penetration in the composite material takes place by means of the pins of the connecting element. An example for the successful penetration of composite materials with low damage to the fibers is given in [8]. At the same time, pins with rather sharp angles of sharpening, about 10 degrees are used as a tool. However, the subsequent process of resistance spot welding does not allow the usage of pins with such a sharp peak and requires an increase in sharpening angle of more than 50 degrees.

First investigations showed that not only the pins with small angles of sharpening have a positive effect in the process of penetration, but the small diameter pins do too. (Fig. 1)

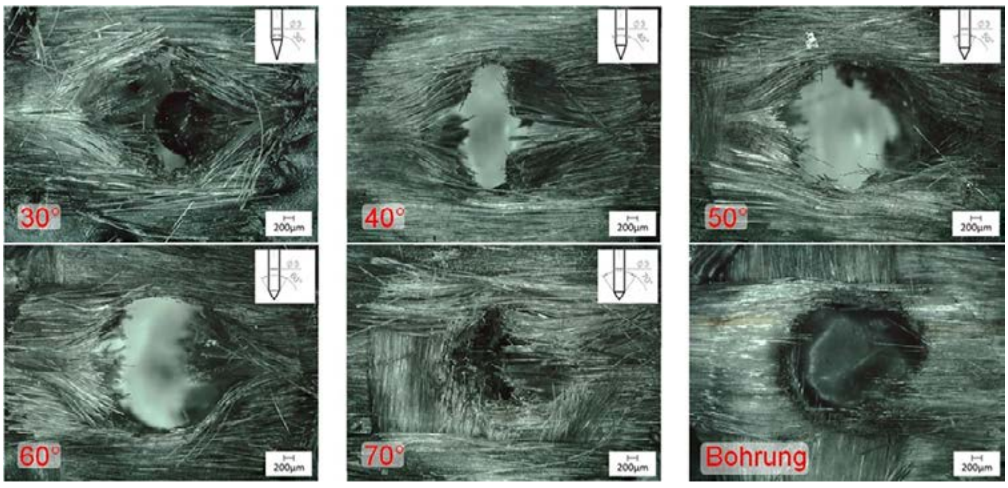


Fig. 1. Fibers damage at various angles of pins sharpening with 3 mm diameter compared to the drilled holes (lower right) (material PA6-GF47)

The investigations also revealed that even after the pins outlet on the back side of the composite material, there is also a partial pressing of fibers and plastic matrix, which is negative for the welding process and also deteriorates the contact. This negative effect could be eliminated by means of the use of additional stop pins at the outlet side of the composite material. This significantly reduces the amount of extruded material and thus provides favorable conditions for the subsequent welding process.

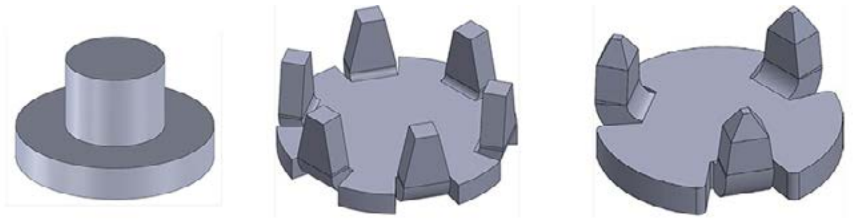
Resistance element welding

Nowadays, the process of resistance element welding (Fig. 2a) has already been introduced and is used in the automotive industry for the connection of steel and aluminum. Within the present studies, it was the task to design an element which is produced in a process combination of stamping from a steel sheet metal and a forming process afterwards. Figure 2 b shows the investigated prototypes who is used for a series of weldability studies as well as for shearing tests. The Element is made from high-strength steel HCT 780+Z and has six contact points. The production of the prototypes on the stage of trials is made by laser cutting, which receives their shape during subsequent machining. A further development of this series is an element with three contact points, presented in figure 2 c. The detailed list of the all materials that were used and their function are shown in the Table 1.

The formation process of a joint with the help of an additional element could be divided into two stages (Fig. 3). In the first stage, the penetration of the element pins into the composite material is made, where in the second stage, the welding to the base material is made.

Apart from the pin penetration technology through the composite material, it is also necessary to develop and optimize the welding technology of pins with the base metal. A main task is to minimize the heat input into the composite material in order to avoid a thermal damage to the fibers and the matrix of the composite material. This effect is possible with a substantial reduction of the welding time and an increasing the welding current at the same time.

Later, the represented welding results with the technique of the concentrated energy input were obtained with the help of a stationary welding machine provided by Nimak. The specific peculiarity of this machine is the improved Transformer (1kHz MFDC). This transformer allows to use short impulses with a high density of welding current due to the highly increased welding currents. Such welding technique allows getting the concentrated energy embedding into the welding area and to minimize thermal influence on the composite material. Besides the improved welding transformer, the welding machine also has the hybrid follow-up unit called "Magnetic Drive", which in its turn allows getting a high speed of electrode contraction during the welding process with a maximum electrode force of 10 kN. Figure 4 represents the measured parameters of a welding process of composite material with steel by means of an auxiliary element.



a: rotationally symmetric element (already in use) | b: element type B with 6 pins | c: element type C with 3 pins

Fig. 2. Different geometrical forms of the elements for resistance welding

Table 1. Representation of the used materials und its function

	thickness	material	function
22MnB5+AS150	1.5 mm	steel	base metal
HCT 780+Z	1.5 mm	steel	element material
PA 6	2.0 mm	thermoplastic	current range determination
PA6GF47	2.0 mm	FRP	mechanical property determination

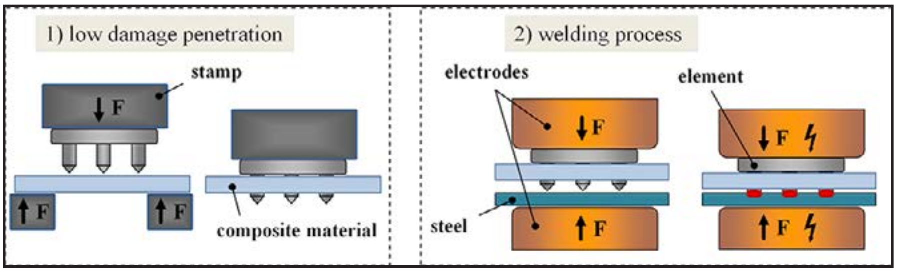
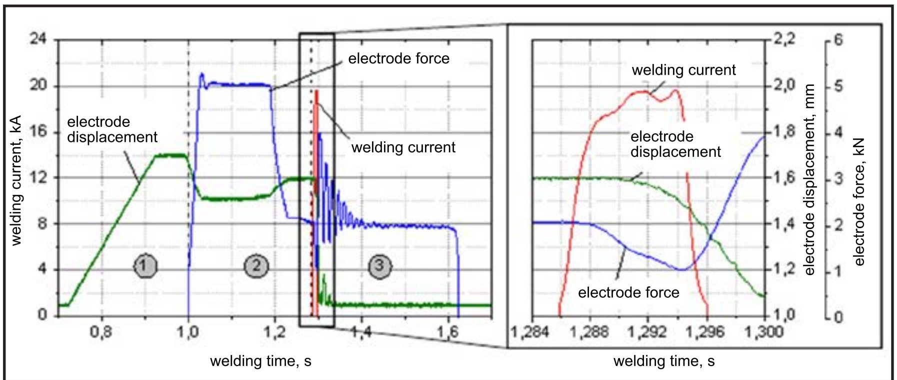


Fig. 3. Two-stage formation of the welded joint with an additional element



welding current	welding time	electrode force	squeeze force	squeeze time	hold time
19,5 kA	10 ms	2 kN	5 kN	200 ms	300 ms

Fig. 4. Resistance welding measured parameters by means of the auxiliary element B

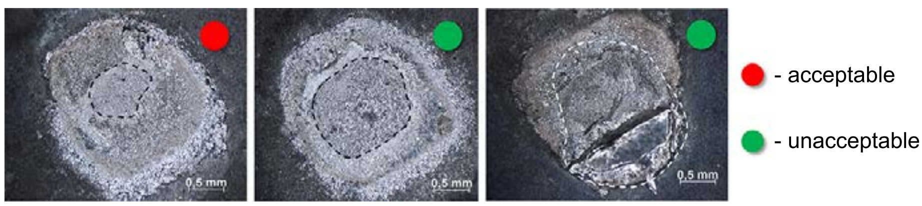
The whole welding process could be divided into three areas. In the 1st area, the pre-compression of details appears by means of the welding electrodes. In this case, a high electrode force (5 kN) was used to improve the electric contacts. Further, in the 2nd area, in order to avoid high deformations during the welding process the electrode force was reduced to 2 kN. In the 3rd area, the welding process and permanent connection occurs. The peculiar role in the process has the stability of the electrode displacement. Due to the short welding time of 10 ms, in the moment were the welding current transitions, rapid heating and fire polishing of the elements pins appears. Therefore, it is demanded to have the high speed of compressing electrodes in order to have the constant electrode compression magnitude.

Determination of a welding current range

Technical standards and regulations developed for the process of resistance spot welding, in particular for determining the quality of the obtained welded connections, can only be partially used for welding of auxiliary elements. The main reason is the lack of a welding nugget in the joint which is the main criteria in quality control because of a very short welding time. Thus, due to the above restrictions, at the moment it is necessary to develop a method for the quality determination of welded joints, and also for the range determination of applicability of the welding parameters.

In order to determine the lower limit of welding parameters, destructive testing was proposed. The main reason of this method lies in the analysis of the resulting fractured surface. The joint is classified as acceptable when during the test the composite material is destroyed and auxiliary element stays welded to the base material. If a failure occurs in the joint with the steel pin, the fracture surface is analyzed (Fig. 5). In the case of a partial interface fracture (Fig. 5 c), when there is a partial separation in the fusion line and also a break in the pin, the compound is also considered to be acceptable. However, at the interfacial fracture (Fig. 5 a and b), the area of the fusion zone would be the determining factor. According to SEP 1220-2 and DIN EN ISO 14327, metal splashes during the welding process are considered to be unacceptable criterion. According to this criterion, the upper limit of welding parameters is defined. In the case of auxiliary element contact welding with very short welding time, this criterion is not feasible, since already at low currents metal splashes can form, and with increase of current, the splash intensity increases. Therefore, the upper limit of determination was made on the bases of the adapted quality criterion. Thus, in the case of heavy burn-out in the zone of pin junction with the base metal, or the strong thermal damage in the composite material and massive emission of molten metal during welding – the upper limit is considered to be achieved.

To ensure a stable welding process a wide welding current range must be achieved. This area should not be less than 1.2-1.5 kA. When determining the lower limit, based on the above described criteria for determining the quality of the connection, the fivefold iteration of the test should be made in order to conduct a statistical test result. After receiving the lower limit makes the stepwise increase in the welding current by 0.2 kA until the upper limit is reached. As in the case with the lower limit, reaching the upper limit of the welding range should be also proven by the fivefold iteration welding test.



a: interfacial fracture; bonding area is too small | b: interfacial fracture; bonding area is sufficient | c: partial interface fracture; bonding area is sufficient

Fig. 5. Fracture surface after the destructive testing (chisel test)

Results

The low-alloyed and press hardened manganese-boron steel 22MnB5+AS150 with aluminum-silicon coating (t=1,5 mm) was used as the base metal. The auxiliary element was made of HCT780+Z with zinc coating (t=1,5 mm). Two materials were used as cover sheets. The first is the composite PA6-GF47 with t=2 mm and 47% of it is glass fiber, moreover, a matrix of the composite consists of thermoplastic. The strength of the composite is 605 MPa lengthwise and 125 MPa crosswise the fibers. As a second material a thermoplastic PA6 (t=2,0 mm) was used, which is identical to the matrix material of the composite. The purpose of using this material is mainly in the reduction of the cost of tests for the optimization of the welding process and defining the range of welding parameters.

Received welding current ranges

As it was mentioned above, for the investigation of the welding parameters and definition of their limits, the combination of 22MnB5+AS150 and thermoplastic PA6 was used. During all the tests, the prior electrodes force of 5 kN was used, as well as 2 kN during welding. Thus, the limits of the welding current range were obtained experimentally, presented in Figure 6, for the welding times of 10, 12 and 14 ms respectively.

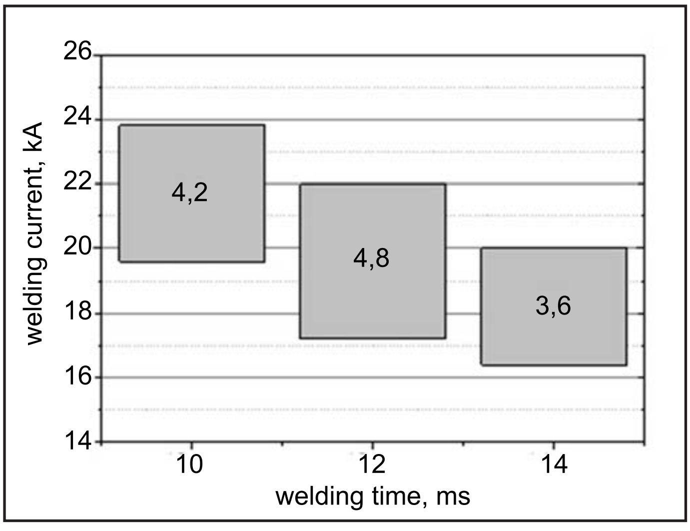


Fig. 6. Received welding current ranges for different welding times with 22MnB5+AS150 and PA6 material combinations used and auxiliary element with B-form

From the above mentioned diagram, it follows that by increasing the welding time there is a decrease in the welding current. It can also be noticed that for a welding time of 14 ms, the size of the welding current range has the lowest value. As mentioned above, the definition of the welding current range was carried out not in accordance with accepted standards and norms, but based on the subjective evaluation criteria such as the nature of the break under the destruction quality control method, metal emission intensity from the welding zone, burn-out in the composite material, or strong deformation of the auxiliary element during welding.

Figure 7 shows a welded sample of 22MnB5+AS150 and the thermoplastic PA with usage of an auxiliary element. Also, the microsection of one of the pins, welded to the base metal, is represented. Based on the results of metallographic studies, formation of a liquid core in the joint, which connects the two metal samples, has been established. In contrast, the microstructure of the base metal as well as a connecting pin indicates that the compound was obtained in a solid state without forming a liquid phase. Thus, it can be concluded that the modes with a very short welding time (10-14 ms) prevent the formation of a liquid core, and the formation of the compound occurs in the solid phase. Also, attention should be paid to a very small size of the heat affected zone (HAZ) in the base material (Fig. 7) and the minimum thermal effect on the thermoplastic. This effect is also caused by an increase in the welding current density due to the shortening of the time and an increase in welding current. This allows moving a concentrated heat to the welding zone, avoiding strong thermal effects to the base material or to the thermal sensitive composites, which is certainly a positive result.

The strength and mechanical properties of REW's

The results of the quasi-static tensile shear tests are given in Figure 8. In this tests the joint strength at the lower and upper limits of the welding current range for welding times of 10 and 12 ms were examined. The test conditions based on the standard DIN EN ISO 14273. The composite material PA6-GF47 and the element with form B were used within the test. The welding of the tensile shear test specimen was carried out with the element form B and predrilled holes within the fiber-reinforced composite material.

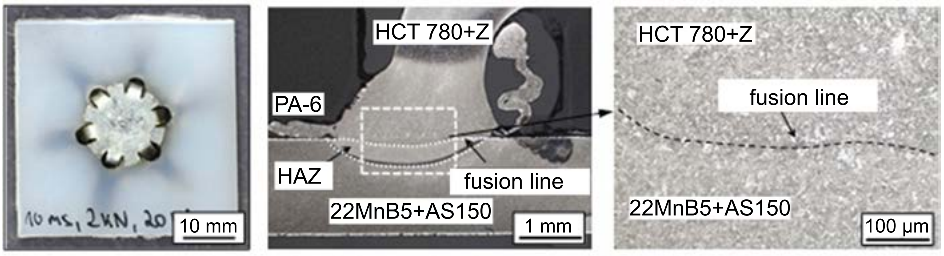


Fig. 7. Welded sample with element form-B and microsection of one of its six connection pins

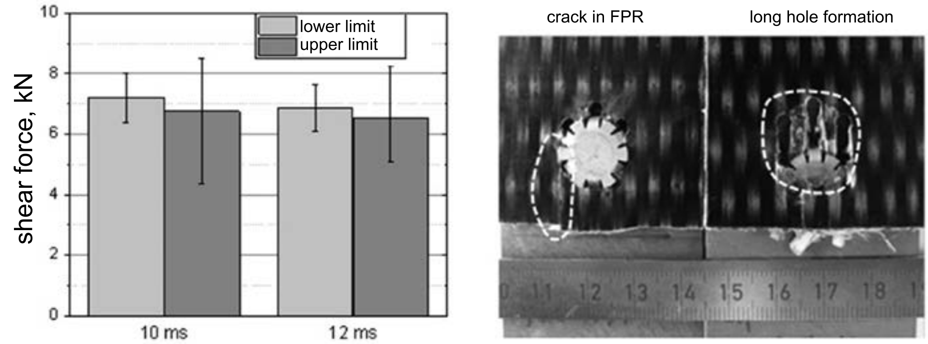


Fig. 8. The resulting values of strength and types of connection distraction from 22MnB5+AS150 and PA6-GF47 with an auxiliary element B

In most cases, the fracture occurred in the composite material (Fig. 8 right), while the auxiliary element remained welded on the steel. Therefore, the overall strength of the connection could not be determined. However, the received strength of the joint was on average 6.5-7 kN and is mainly determined by the strength of composite material. It also should be noticed that the range of the results scattering is quite large (up to 4 kN). The reason for the low reproducibility of the results is the difference in the types of damage in composite material.

Conclusion

Resistance welding with an auxiliary element is an innovative way of connecting a variety of materials with high strength steels. The use of special regimes with very short welding times allow a very concentrated thermal energy input into the welding zone. In this case, because of the short welding time, there is no liquid phase and the formation of a connection occurs on the solid phase. This allows to minimize the thermal effect on the base metal and to avoid the damage to the matrix and the composite material fibers. However, today, there are no clear criteria assessing the quality of such compounds in the regulations and recommendation of materials, which requires further research in this direction. The Institute also requested for detailed studies on this topic [10].

In this article, relying on such standards as the SEP 1220-2 and DIN EN ISO 14327, a method was proposed, as well as a number of criteria for determining the area of the welding current. During the research, sufficient welding current ranges for welding times of 10, 12 and 14 ms, were obtained, which rather proved high technological effectiveness of the process. Mechanical test results with the tensile shear test showed that the connection strength depends on the fracture type of the composite material.

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