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Hybrid Welding of Metal-Polymer Composites with a Non-Conducting Polymer Layer

Abstract: Metal-polymer composites (MPCs) are becoming increasingly popular primarily because of their high strength-to-weight ratio. Metal-polymer composites consist of three layers, i.e. two external metallic sheets (linings) and the core made of plastic. The presence of the internal plastic layer makes MPCs impossible to join using conventional welding processes, which significantly limits their usability. One of the solutions to the problem involves the use of hybrid methods, e.g. ultrasonic method-aided resistance welding. The research work discussed in the article involved the development of a prototype test rig and a technology enabling the joining of the Litecor® composite with steel DP600. The joining process consisted of two stages. The first stage involved the removal of the non-conducting layer of polymer from the welding area and the making of an appropriate electric contact for resistance welding. The second stage was the classical resistance spot welding process. The development of the concept posed a challenge as it was necessary to develop an appropriate acoustic waveguide for high-power ultrasonic waves which, at the same time, could transfer loads in the form of electrode force as well as provide appropriate electric and thermal conductivity without compromising acoustic parameters during the welding process. The development of the test rig was followed by the performance of numerous tests aimed to identify the appropriate window of process parameters. Test joints were subjected to macrographic, strength, ultrasonic and topographic tests.

Keywords: metal-polymer composites (MPCs), Litecor®, resistance spot welding, joining, ultrasounds

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Introduction

Metal-polymer composites (MPCs) are characterised by numerous advantages, particularly important for manufacturers of lightweight structures. The aforementioned advantages include light weight (in comparison with that of steel) without compromising high mechanical properties, workability based on standard cold forming processes and lower manufacturing costs if compared with those related to the production of competitive aluminium alloys. The above-named advantages make metal-polymer

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composites particularly popular with the automotive and aviation industries. An issue precluding the immediate implementation of MPCs was the lack of appropriate technologies enabling the joining of such materials with other materials (e.g. steel or aluminium) or with themselves. The conventional thermal joining techniques (arc and laser welding or resistance welding) were inapplicable due to the presence of the polymer layer. In turn, alternative technologies (such as clenching or punch riveting) failed to provide the proper quality of joints. A technological challenge posed by metal-polymer composites was their joining by means of thermal techniques. The joining of composite materials with metallic alloys is rather demanding and, currently, performed using mechanical fixing or adhesive bonding [1–4]. However, the above-named methods are characterised by certain disadvantages, particularly problematic in industrial manufacturing processes, i.e. stress concentration, delamination during processing, complicated and expensive process automation or, as regards adhesive bonding, significant surface preparation-related requirements, long solidification and problems with surface tension [2, 3, 5].

Because of its significant application potential and numerous advantages, resistance welding can be used to join elements made of composite materials. However, the presence of the plastic core poses a challenge as regards the resistance spot welding process. In spite of the foregoing, producers of composites maintain that the resistance welding of MPCs is possible [4, 6–8] (which was confirmed in numerous research works). Some publications [1, 3, 9] emphasize that the resistance spot welding of MPC laminates is impossible without modifying the joint and, following producer's advice, suggest the use of a third electrode (the so-called shunt), indispensable for heating the joint area, plasticising the polymer and obtaining electric contact between the two layers of metal.

One of the most detailed studies concerning the subject is contained in an article by I.K.A Al Naimi et al. [10]. The study discusses the possibility of using a shunting element in the resistance spot welding of the Litecor® material with steel DP800. The Authors describe the optimum technological parameters (electrode force, welding current, welding time, number of impulses and the distance between the electrode and the shunting element) as well as joint-related test results (obtained in measurements of shear breaking load, hardness measurements in the fusion zone and in the HAZ as well as macro and micrographic tests and SEM/EDS tests).

Shunt current-aided resistance spot welding was also analysed by J.S. Tanco et al. [11]. The authors developed a technology making it possible to perform the spot welding of three sheets (i.e. a 1.5 mm thick sheet made of steel DC06 (1.5 mm + 0.8 mm thick sheet made of Litecor® 0,8 mm + and a 1.5 mm thick sheet made of steel DC06 1.5 mm) and obtain joints characterised by required quality. Numerical simulations were performed in the SORPAS® 3D software programme. The diameters of modelled spot welds were compared with experimental test results. The results presented in both articles [10, 11] indicated a significant industrial potential of the joining method, yet the obtainment of joints representing good quality requires the thorough control of the welding process and its parameters. Attempts have also been made at using the resistance welding process to join non-metallic (i.e. non-conducting) composite materials with metal alloys. Many research works indicate that the aforesaid process can be used successfully by applying an additional heating element (characterised by higher resistance) – usually a mesh made of stainless steel, located in-between the sheet contact [12].

As presented above, the resistance welding of MPCs with solid metallic materials is possible after modifying the conventional resistance welding method. This article presents a method which offers the advantages of classical joining methods (e.g. short processing time and low unit costs) and, at the same time, overcomes their limitations when it comes to joining advanced MPC materials.

Test materials

The tests involved the use of a material having the commercial name of Litecor® and produced by ThyssenKrupp Steel Europe. In terms of its weight and in relation to economic aspects, Litecor® is a compromise between steel and aluminium [3, 6, 17]. Figure 1 presents the schematic diagram of the Litecor® material used in experimental tests.

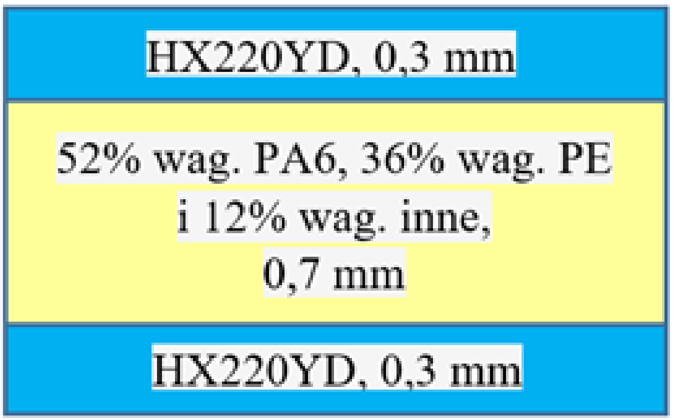

Fig. 1. MPC Litecor® used in the tests

The Litecor® composite is characterised by tensile strength restricted within the range of 190 MPa to 240 MPa (confirmed in individual tests, Rm = 230 MPa) and a yield point restricted within the range of 120 MPa to 180 MPa in relation to elongation A80 approximately 28% [9, 18]. Litecor® consists of three layers (Fig. 1) obtained in the hot adhesive bonding process [3]. The external layers (having a thickness restricted within the range of 0.2 mm to 0.5 mm) can be made of steel HX220YD (in accordance with EN 10346), steel HC220Y (in accordance with EN 10268) or steel CR210IF (in accordance with VDA 239-100), i.e. cold-formed high-strength interstitial-free (IF) steel [3, 4, 7, 9, 17, 18].

The material of the external layers is additionally protected against corrosion with zinc coating ZE75 or ZE50 [4, 18]. The internal layer of the polymer core was the mixture of polyamide/polyethylene (0.3–1 mm), composed of 52% by weight of PA6, 36% by weight of PE and 12% by weight of other additions [3, 4, 7, 9, 17, 18]. In terms of joints, important properties of PE/PA compounds include a melting point of 220°C, a solidification point of 192°C and breakdown temperature above 300°C [18]. Litecor® is made in two variants, i.e. Litecor® C (classical) and Litecor® S (strong) [9, 18].

Table 2 presents the chemical composition of steel HX220YD (used to make external layers) and of steel DP600 (joined with the Litecor® composite).

Table 2. Mechanical properties of steel HX220YD (in accordance with EN 10346) and DP600 (in accordance EN 10338)

Property	**$R_{0.2}$, MPa**	**R_m, MPa**	**A_{80}, %**
HX220YD	220–280	340–420	32
DP600	340–420	600	20

The Litecor® laminar material was joined with a 0.8 mm thick sheet of steel DP600. Steel DP600 is cold-rolled dual-phase steel containing soft ferrite (responsible for favourable formability and hard martensite (responsible for high strength). The formability of steel DP600 makes it usable in the manufacturing of deep drawing elements. The steel is characterised by good weldability and can be used in the production of car safety features (e.g. crumple zone or pillars A and B). The chemical composition of steel DP600 is presented in Table 3.

Table 1. Chemical composition of steel HX220YD (% by weight in accordance with EN 10346)

C max.	Si max.	Mn max.	P max.	S max.	Al max.	Nb max.	Ti max.	Cu* max.
0.01	0.2	0.9	0.08	0.025	0.1	0.09	0.12	0.2

* in accordance with VDA 239-100

Table 3. Chemical composition of steel DP600 (% by weight, in accordance with EN 10338)

C max.	Si max.	Mn max.	P max.	S max.	Al max.	Cr+Mo max.	Nb+Ti max.	V max.
0.17	0.8	2.2	0.08	0.015	2	1	0.15	0.2

Methodology and test rig

The primary obstacle which accompanies the resistance spot welding of MPCs is the presence of the non-conducting polymer core, limiting (or even preventing) the flow of electric current through the material. To ensure the flow of current through the external sheets, the non-conducting polymer must be removed at the first stage of the process. The research involved testing the removal of the non-conducting layer using high-power ultrasonic waves. The aforesaid method aimed to remove the non-conducting polymer layer from the welding area and create appropriate electric contact for the resistance welding process. The concept of the method is presented in Figure 2.

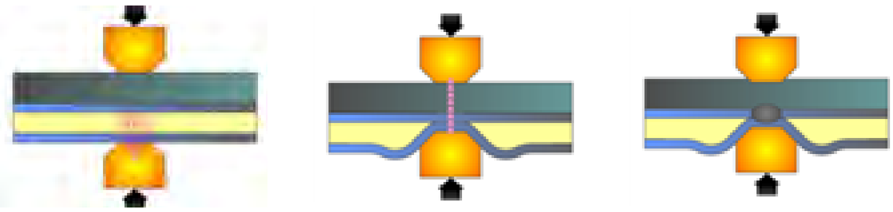

Fig. 2. Schematic diagram of the technology enabling the joining of MPCs: a) ultrasonic heating, b) plasticisation and formation of the polymer layer and c) resistance welding

The ultrasound-aided resistance welding process (Fig. 2) involves the combination of two physically different methods in which materials are heated during one welding cycle, at two successive stages. At the first stage, the polymer core is heated by high-power ultrasonic waves and the polymer is formed through the exertion of welding machine electrode force. The second stage involves the flow of welding current. Current flows through the “cleaned” joint area containing electric contact of MPC layers. The layers are heated and a permanent joint of the MPC with the solid material (steel DP600) is obtained. To utilise the effect of ultrasonic waves on the polymer core of the metal-polymer composite, the welding circuit was expanded to include a high-power “sandwich” type ultrasonic transducer. The lower electrode was used as the so-called sonotrode and a special electrode, supplying welding current to the contact between the sheets. The lower electrode was made of a cylinder (with the diameter of the grip part amounting to 40 mm) bolted with a vibrating system. On the work surface side (being an integral part of the sonotrode), the sonotrode shape was similar to that of typical welding caps, e.g. form FB or FE (in accordance with ISO 5821/DIN 44750). The type of work surface geometry is adjusted in relation to the thickness and the type of the MPC material and the required diameter of the weld nugget. The counter electrode (anvil) used in such processes is usually a typical welding cap, e.g. FB or FF (in accordance with ISO 5821/DIN 44750) (Fig. 3).

The sonotrode (put into vibration by the high-power ultrasonic system) was connected with the electric circuit of the resistance welding machine. The welding station was composed of an ultrasonic transducer having a resonant frequency of 20 kHz and a maximum power of 3 kW and of the so-called booster (i.e. an intermediate element between the transducer and the tool (sonotrode)). The geometry of the booster was designed so that its rigid attachment to the busbar would not dampen the ultrasonic vibration of the working tool. The sonotrode, mechanically coupled with an amplifier, was the key element of the system.

The resistance welding machine used in the tests was a technologically advanced inverter welding machine having an operating frequency of 10 kHz, an active power of 40 kVA and electrode force restricted within the range of 0.8 kN to 3.5 kN (Fig. 3).

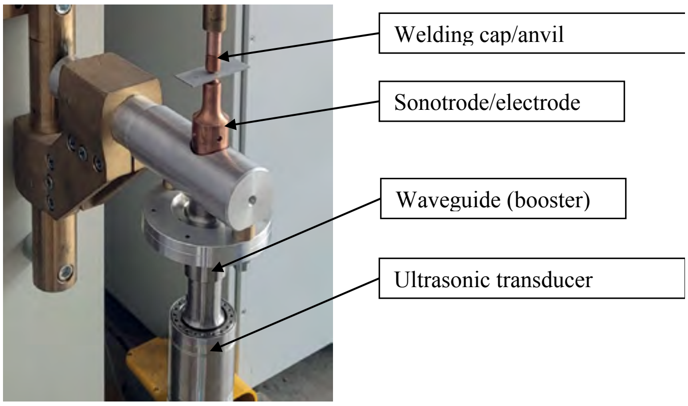

Fig. 3. Test rig – ultrasonic system-aided welding window

The developed method aimed to eliminate the limitations of other joining methods, reduce heating time, decrease the degeneration of the material of MPC external layers and increase the conductivity of the electric contact of the electrodes with the material and the external layers.

Test results

The first stage involved the adjustment of the parameters of the heating process and those of the formation of the MPC polymer core. During the aforesaid stage it was important to pay attention to the appropriate temperature characteristics of polymers, i.e. polymer glass transition temperature Tg and plasticisation temperature Tp (Table 4). Related analyses revealed that the proper implementation of the ultrasonic heating method enabled the obtainment of temperature above Tp (for the mixture of PA and PE) and, as a result, the formation and the effective removal of the polymer layer from the welding area.

An important feature of the ultrasonic method of polymer formation is the heating rate. In comparison with other methods (e.g. direct heating or current shunting), thermal energy is generated inside the polymer layer. The problem of low thermal conductivity is not so important that it should be extended to ensure the flow of heat in the polymer and its uniform distribution. This provides significantly more favourable conditions for the flow (removal) of the polymer layer from the welding area (important in terms of the technology). Figure 4 presents the Litecor® composite with the polymer core removed using ultrasonic waves.

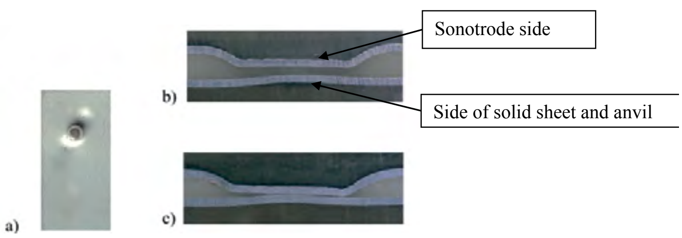

Fig. 4. Removal of the polymer core using ultrasonic waves: a) joint surface, b) cross-section after the incomplete removal of the polymer core and c) cross-section after the removal of the polymer layer

As mentioned above, first it was necessary to adjust ultrasonic heating parameters to obtain electric contact between external steel layers and the MPC material and enable the flow of welding current through the joint contact area (Fig. 4b and 4c). Failure to properly perform the above-presented stage (i.e. failure to obtain the electric contact of the surface layers) could result in two cases.

In the first case, welding current does not flow and the joint is not formed. In such a situation it is possible to repeat the ultrasonic process in order to obtain proper contact and make a joint. In the second case, where some welded joints have already been made or there is even slight electric contact outside the welding area, the shunting effect could occur. The latter case is particularly unfavourable and dangerous for elements being joined. Welding current flows

Table 4. Characteristic temperatures for selected polymers [19]

Material	Polyethylene	Polyamide (PA6)	Polypropylene
Glass transition temperature Tg [°C]	-125	50	-10
Plasticisation temperature Tp [°C]	110	225	165

through the layer of the MPC coating, which could lead to the overheating, delamination, deformation and even the entire loss of MPC material continuity. In addition, also the protective (e.g. zinc) coating covering the MPC could be damaged. For these reasons, it is necessary to effectively monitor the process of polymer removal and the moment when electric contact is obtained. The monitoring process can be performed using classical measurements of motional resistance (during ultrasonic heating). The use of low welding current impulses (i.e. not to damage or significantly heat materials being joined) could enable the effective monitoring of the process. It is also possible to provide feedback to the ultrasonic generator in order to obtain information on when the heating process is finished and the resistance welding process can be started.

During the adjustment of ultrasonic heating parameters it was necessary to reduce (as much as possible) the duration of the process in order to decrease the risk of damage to the joint or the delamination of the polymer core of the MPC. The UT+RSW joining process (ultrasonic + resistance spot welding) was performed in relation to three welding times, i.e. 150 ms, 250 ms, 1 s and in relation to 5 various voltage amplitudes exciting the ultrasonic transducer, i.e. 10%, 20%, 30%, 40% and 50%. The maximum voltage amplitude for the transducer amounted to 1800 V (Table 6). During the tests, two configurations were taken into consideration, i.e. the use of the ultrasonic transducer on the side of the solid material and another on the side of the MPC material.

The analysis of Table 6 revealed that the common parameters for both configurations were voltage U = 720 V (40%) and vibration time T = 250 ms.

The resistance welding process was performed using the two-impulse welding programme. The first impulse was used to remove the layer of impurities and zinc layers from the contact surface of the materials being joined. In addition, the use of the first impulse enabled the measurement of motional resistance and verification whether the resistance welding process could be performed safely and properly. The second impulse was used to make a proper weld joining all sheets. Welding parameters (Table 7) were selected so that it was possible to obtain the maximum weld nugget diameter during the shortest possible time of the process. The tests also involved the listing of welding imperfections in the welds such as the unacceptable condition of the joint surface, the presence of cracks, the condition of protective coatings, the results of expulsion etc. The average weld nugget diameter of the joints obtained in the tests amounted to 5.3 mm, whereas their average tensile strength (identified in a static tensile test) amounted to 3.2 kN.

The subsequent stage involved the metallographic tests of the joints. The specimens were etched in 2% Nital. The macro and microstructural observations of the joints revealed that it was possible to make joints free from imperfections (Fig. 5) such gas pores, inclusions and

Table 6. Adjustment of parameters used during the heating of the polymer core

Configuration	**MPC on the sonotrode side**			**DP600 on the sonotrode side**		
U [V] / T [s]	0.150	0.250	1	0.150	0.250	1
10%	0	0	0	0	0	0
20%	0	0	x	0	0	x
30%	0	x	x	0	0	x
40%	x	x	x	0	x	x
50%	x	x	x	0	x	x
X – electric contact, 0 – lack of electric contact						

Table 7. Selected welding process parameters

	Electrode force F [N]	Welding current [kA]	Current flow time [s]
First impulse	1000	3.1	0.15
Second impulse	1000	5.5	0.15

other discontinuities. The heat affected zone (HAZ) was very narrow and the polymer core was formed properly. The most common imperfections (connected with the use of overly low current parameters in the resistance welding process) were lacks of penetration of all the metallic layers.

Fig. 5. Proper weld with the weld nugget and the HAZ

Conclusions

The research-related tests aimed to present an innovative technique enabling the joining of technologically advanced materials i.e. metal-plastic composites (MPCs). The tests involved the use of the material having the commercial name of Litecor® and steel grade DP600. The test rig composed of an inverter spot welding machine and an ultrasonic transducer (developed by the Authors) enabled the joining of materials which, at the first stage of the process, were not characterised by electric current conductivity. The use of the high-power ultrasonic system enabled the classical resistance spot welding of MPCs.

In addition, it was possible to formulate the following conclusions:

- risk of MPC material degradation can be minimised by using a multi-pulsed welding programme. Such a method enables the removal of the protective layer and impurities from the welding area;
- most frequent welding imperfection in the joints were lacks of penetration in the MPC external layers;
- ultrasound-aided welding of Litecor® polymer composites with steel DP600 was a process where ultrasonic heating occurred locally in the polymer core. The foregoing led to the formation of local flash, i.e. a buffer indispensable for the collection of excess polymer material. A certain limitation of such a process could be the thickness of the removed polymer core. The overly low amount of excess polymer could result in the breaking of the coating layer of the material. The above-named problem did not occur in relation to 1.3 mm thick Litecor®.
- developed method can be successfully automated and robotised. The solution presented in the article enables the obtainment of proper welded joints of the Litecor® material and steel DP600. Further combinations of materials and modifications of the technology will be tested and discussed in detail in subsequent research.

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