CLINCHING AND RESISTANCE SPOT WELDING OF THERMOPLASTIC COMPOSITES WITH METALS USING INSERTS AS JOINING INTERFACES

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ABSTRACT

Suitable joining systems are an important factor for the successful application of thermoplastic composites (TPC) in multi-material systems. In industry in particular, there is a demand to reduce the number of different joining processes despite the increasing diversity of materials. In order to use established metal joining technologies, such as clinching or resistance spot welding (RSW), for composite-metal joints, auxiliary joining elements (inserts) can be integrated into the composite and used as joining interfaces. The metal inserts can be embedded into TPC during the part manufacturing process using a pin tool without damaging the reinforcing fibres. Subsequently, the composite part can be joined with aluminium or steel structures using either clinching or RSW. For this purpose, inserts differing in their geometries suitable for either clinching or RSW have already been investigated. In this paper, a versatile insert geometry is evaluated that is suitable for both joining processes. The development of the inserts was supported by process simulations and took into account the specific requirements of both joining processes. Inserts were embedded in glass fibre reinforced polypropylene sheets and then joined to metal sheets. The quality of the joints was analysed by microsections. In addition, the joint strength was evaluated by single-lap shear tests for the different joining technologies. It could be shown that high-quality clinched and welded joints can be achieved by using the developed versatile insert geometry as joining interface.

1 INTRODUCTION

Thermoplastic composites (TPC) are an integral part of modern lightweight designs due to their excellent specific mechanical properties, recyclability, reprocessability and efficient manufacturing processes [1]. Joining is usually a key enabler for a successful application of TPC components in multi-material systems. However, joining technologies developed specifically for TPC are often not adapted to the process chains of series production. In addition, automotive manufacturers intend, for example, to keep the number of different joining techniques as small as possible in order to reduce complexity and increase efficiency [2]. Clinching as mechanical joining process and resistance spot welding (RSW) as thermal joining process are standardized technologies, which are widely used for sheet metals [2-4]. However, due to the different physical and mechanical properties of the dissimilar materials [5,6], such as ductility and melting temperatures, they cannot directly be used for TPC-metal joints.

The general clinchability depends especially on the ductility and the tensile strength of the joining partners [7]. Because of the lower ductility of TPC, as well as the limitations caused by continuous fibre reinforcement, conventional clinching is challenging for hybrid TPC-metal joints. Current research efforts are pursuing various approaches to integrate TPC into multi-material structures using advanced clinching techniques. For instance, when clinching materials with low ductility or high tensile strength, a pilot hole can be integrated into the less ductile joining partner [8-11]. In addition, several authors have taken up the promising approach of increasing the formability of TPC by heating it up. Therefore, process-integrated heating [12-14] as well as friction [15] can be used. Another approach, already presented by the authors, is to use metal inserts in the TPC components as interfaces for clinching [6]. These metal inserts can be embedded into TPC during part manufacturing process according to the principle of moulding holes by a tapered pin tool in a plasticised state of the TPC [16]. In this way, the reinforcing fibres are not cut by punching or drilling, but shifted aside. Afterwards the composite part with the embedded clinch inserts can be joined with metallic components in a clinching process using standard tools without damaging the reinforcing fibres of the TPC [6]. During the clinching process, the clinch insert and the metallic joining partner are deformed, while the TPC remains undeformed. Both rigid and opening dies are applicable and the TPC can be positioned on the punch side as well as on the die side [6], which contributes to flexibility in the application.

The approach of using additional metal elements as joining interfaces to overcome the incompatibility of the joining partners is also used for RSW of dissimilar materials [17]. These interfaces can be integrated into composites during or after the part manufacturing process. For thermoset composites, for instance, Joesbury et al. [18] applied prior to the infiltration process a metallic intermediate plate in the joining zone and Roth et al. [19] integrated a flat weld insert during preforming into the composite. Furthermore, the principle of resistance element welding, which was developed for joining low-ductile (e.g. aluminium) and high-strength (e.g. ultrahigh-strength steel) materials [20], can be applied for composites. The auxiliary weld element can be positioned in a pre-hole [17] or directly be inserted by a punching process into the composite component [21]. In addition, the authors developed a technology to embed weld inserts during composite component manufacture in the compression mould without fibre damage [22], in the same way as the described clinch inserts.

The clinch inserts [6] and weld inserts [22] already developed differ in their geometries due to the different specific requirements of the joining processes. In this study, a versatile insert geometry is investigated that is suitable for both joining processes with an identical insert geometry.

2 MATERIALS AND METHODS

2.1 Material Specification and Geometry of the Inserts

The investigations were performed on TPC sheets made of glass fibre reinforced polypropylene (GF/PP). GF/PP is a typical material for lightweight applications with moderate thermal and mechanical requirements. For instance, it is applied for large-scale production of thermoplastic door module carriers [23]. The laminate in this study consists of unidirectional (UD) tapes, which were processed into TPC sheets in an autoclave process. An unalloyed structural steel (S235JR [24]) was chosen for the inserts because of its high availability, good weldability and sufficient formability for clinching. As a joining partner for clinching aluminium EN AW-6016 T4 [25] was selected. On the other hand, a low-alloyed steel (HC340LA [26]) with high yield strength and a good weldabilty was used as joining partner for RSW. The specifications of the utilised materials are summarized in Table 1.

	Parameter	for clinching	for RSW
TPC	Material	Celstran® CFR-TP PP-GF70	
	Configuration	UD $[(0^\circ/90^\circ)_2]_s$	
	Fibre volume content	45%	
	Sheet thickness	2.15 mm	
Metal	Material	aluminium EN AW-6016 T4	steel HC340LA
	Sheet thickness	1.5 mm	1.5 mm
Insert	Material	steel S235JR	
	Insert height	2.15 mm + 0.3 mm	

Table 1: Specification of the utilised materials.

When developing versatile insert geometries, the different process-specific constraints for the embedding process as well as the clinching and RSW must be taken into account. For instance, to ensure embedding without fibre damage, the insert's diameter is limited. For the TPC configuration investigated, previous studies have shown that inserts with a head diameter up to 16 mm, inserted with a 14 mm diameter pin, can be embedded without damaging the fibres [6]. In order to meet the clinchability requirements, the insert should have a large diameter and a limited height. In addition, a welding projection is recommended to ensure weldability. To design the insert geometries, process simulations for clinching and welding were applied. On the one hand, clinching simulations were performed to prove if the projection is levelled during the clinching process so that undesired gaps between the joining parts can be avoided. On the other hand, it was investigated if suitable welding parameters with a short welding time can be found for the inserts in order to keep the thermal load of the surrounding TPC low. In the process simulations, three different projection geometries were investigated for versatile inserts, varying the diameter of the projection (d_{IP}) between 4 mm and 12 mm (Fig. 1).

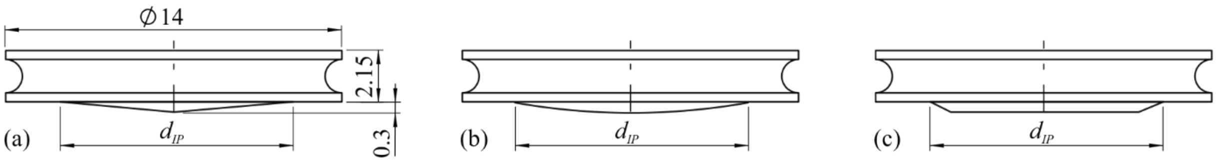


Figure 1: Different projection geometries for versatile inserts: (a) cone, (b) radius and (c) flat dome (all dimensions in mm, with variable diameter of the projection d_{IP}).

2.2 Process-Integrated Embedding of Inserts into TPC

Metal inserts can be embedded into TPC during part manufacturing process using the principle of moulding holes [27,28]. Thereby, a hole is formed by a pin tool and simultaneously the insert is placed in the moulded hole. In this process the reinforcing fibres are not cut by punching or drilling but shifted aside by a tapered pin tool in a plasticised state of the TPC [16]. The process of embedding metal inserts into TPC parts is schematically illustrated in Fig. 2.

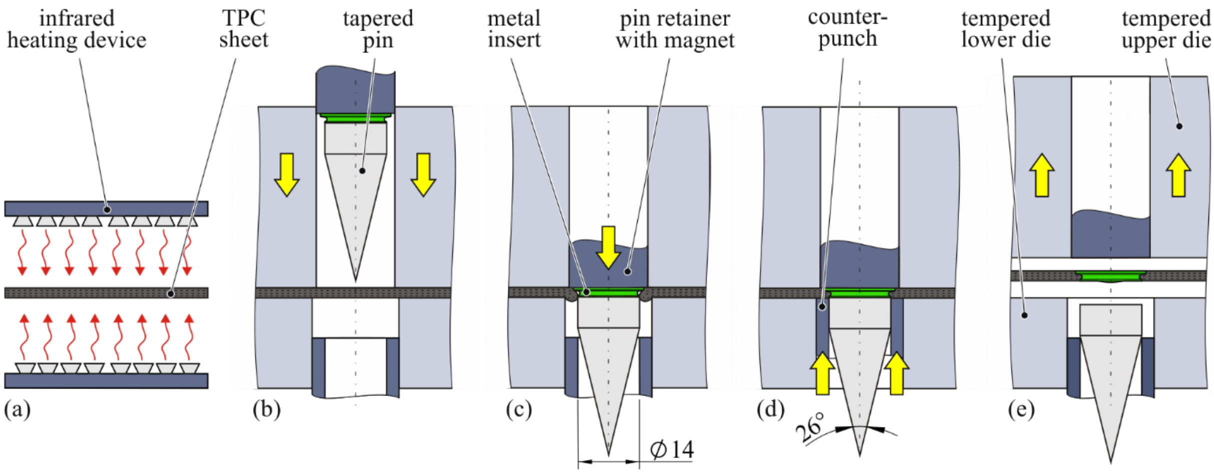


Figure 2: Schematic illustration of the process-integrated embedding of inserts into TPC components during compression moulding: (a) heating up the TPC sheet, (b) closing of the compression mould, (c) movement of the pin tool, (d) recompressing the squeezed-out material by the counterpunch and (e) demoulding of the TPC component.

First, a pre-consolidated TPC sheet is heated up above melting temperature of the matrix polymer by an infrared heating device (Fig. 2a). Subsequently, the TPC sheet is transferred into the compression mould. By closing the tempered mould, the TPC sheet is shaped and compressed corresponding to the mould contour (Fig. 2b). Immediately after closing the tempered mould, a pin tool (consisting of a tapered pin and a pin retainer) is shifted forward, forming a hole by displacing the reinforcing fibres and the still molten thermoplastic matrix (Fig. 2c). The two-parted pin tool contains a magnet to attach the tapered pin and the insert to the pin retainer. Subsequently, after the pin movement, the squeezed-out material is recompressed by a ring-shaped counterpunch whereby the undercut of the insert is filled with fibres and matrix material (Fig. 2d). The embedding of the insert (steps c and d) takes less than one second. After cooling and solidification of the TPC part, the pin retainer is retracted and the tapered pin is separated. Finally, the TPC component with integrated insert is demoulded (Fig. 2e).

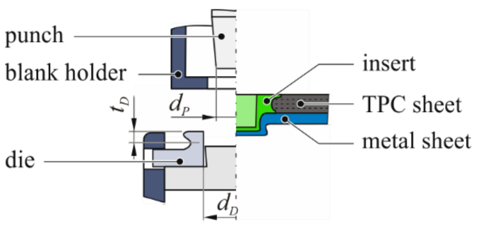
In this study, a pilot rig at the laboratory scale consisting of an infrared heating device and a tempered steel mould was applied to manufacture plane TPC specimens with integrated inserts. The pin tool is pneumatically actuated, such as the counterpunch. The manufacturing parameters were selected according to those used for the embedding of clinch [6] and weld inserts [22], see Table 2. The tapered pin has a diameter of 14 mm and a cone angle of 26° (Fig. 2).

Parameter	Unit	Set value
Heating temperature TPC	°C	210
Mould temperature	°C	40
Feed force of the pin tool	kN	2.5
Feed force of the counterpunch	kN	5

Table 2: Manufacturing parameters of the embedding of metal inserts into TPC sheets.

2.3 Clinching

Clinched joints were manufactured after insert embedding, using a DFG 500/150 machine from ECKOLD GmbH & Co. KG. The C-frame stand machine with hydraulic drive has a stroke-controlled joining cylinder. The limitation of the stroke is realized via the height adjustment of the punch. Conventional clinching tools for metal joints are used. The characteristic dimensions of the clinching tools are summarized in Fig 3. The TPC sheet with the embedded insert can be positioned on the punch side as well as on the die side.



Parameter in mm	Insert positioned on the punch side	Insert positioned on the die side
Punch diameter d_P	5.2	5.0
Initial die diameter d_D	8.0	8.0
Die depth t_D	1.2	1.0

Figure 3: Schematic illustration of the clinching tool and joint with tool dimensions.

2.4 Resistance Spot Welding

Experimental investigations regarding RSW were conducted using a powerGUN 2-C type C-frame welding gun by NIMAK International GmbH. The welding gun has a servo-electrical drive that provides a stroke of 700 mm and a maximum electrode force of 8.0 kN. The machine is equipped with a welding case of the type SK-Genius HWI436WA by Harms & Wende GmbH & Co. KG. which has a constant current control and provides a maximum weld current of 65 kA. Standardized Electrode caps of type ISO 5821-A0-20-20-100 made from CuCrZr material were used.

2.5 Process Simulation

The numerical simulation of the clinching process was carried out using the simulation software Simufact Forming 16.0 from simufact engineering GmbH. A two-dimensional, axially symmetrical model was built. In the process simulation, the tools were assumed to be rigid bodies, whereas the parts to be joined were modeled as deformable bodies. The flow curves of the aluminum joining partner EN AW-6016 T4 and the interface material S235JR were determined experimentally by means of tensile tests and then extrapolated by suitable mathematical approaches. The Voce approach was used for the aluminum material and the Ludwik approach for the steel materials. The correspondingly constructed simulation model was then compared with the results of experimentally conducted preliminary tests and validated on the basis of these.

In addition, the qualification of the developed inserts for RSW was assisted using the numeric simulation software SORPAS® 2D Welding V13.83 Enterprise Edition by SWANTEC Software and Engineering ApS. In this study the welded joint is created between the isotropic metal insert and a steel sheet. In this regard a two-dimensional, axisymmetric simulation model was built according to the experimental setup. The thermal and the electrical properties of the metallic joining partners and the electrode caps were taken from the SORPAS database. The TPC was modelled in a simplified form as a thermal isotropic material. The electrical resistivity (16∗1015 (Ω∗cm)) and the thermal conductivity (0.69 (W/m∗K)) of the TPC were adjusted according to the data sheet values. All parts were modelled as deformable bodies with heat conduction. For the mesh, quadrilateral elements were used. Both models, for clinching and for RSW, are shown in Fig. 4.

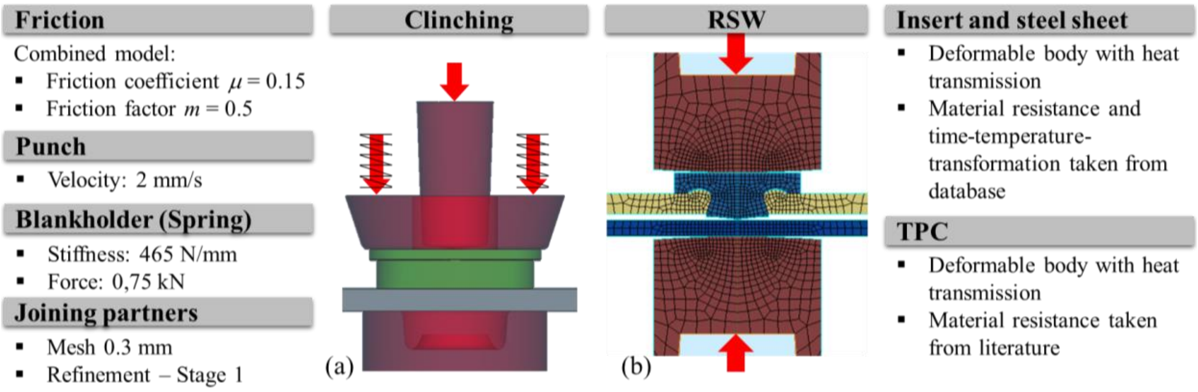


Figure 4: Schematic illustration of the numerical simulation models and their boundary conditions for (a) clinching and (b) RSW.

2.6 Characterization Methods

The joining zones were investigated by micrograph analyses of cross-sections. Characteristic dimensions of a clinch joint are the undercut (*f*), the bottom thickness (t_b) and the neck thickness (t_n), which significantly affect the joint strength and thus the joint quality [29]. Whereas for welded joints, the diameter (d_n) and shape of the weld nuggets are more relevant.

To investigate the mechanical properties of the joints single-lap shear tests were performed on a high-rigid universal testing machine (Zwick Z100, by ZwickRoell AG) at a testing velocity of 10 mm/min. The geometries of the test specimens for the single-lap shear tests are shown in Fig. 5.

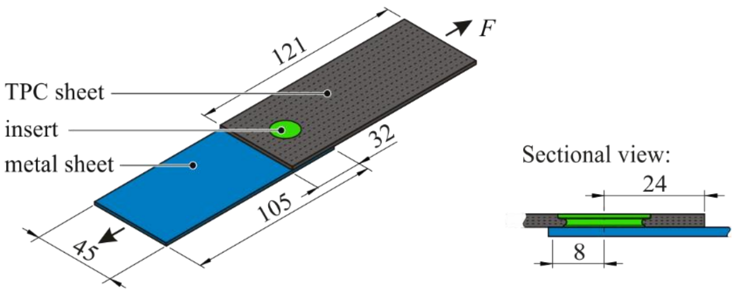


Figure 5: Specification and dimensions of the single-lap shear tests specimens (all dimensions in mm).

3 RESULTS

3.1 Process Simulation

To achieve the versatility of the metal inserts, which enable both clinching and RSW, the joining process specific boundary conditions of both processes were considered. The external characteristics, such as diameter and height, are essentially limited by clinching, since it was shown here on the basis of the preliminary design that an excessively small diameter leads to undesirable deformations of the insert during the joining process. Preliminary investigations have also shown that a weld projection at the base of the insert is required for reliable implementation of the RSW.

The geometry variants shown in Fig. 1 were transferred to the numerical simulation models for clinching and RSW. On the basis of the process simulations, the aim was to investigate on the one hand the extent to which the weld tip is leveled during the clinching process so that undesirable gaps between the joined parts can be avoided. On the other hand, it should be examined whether stable weld areas can still be found with the shortest possible welding time, thus keeping the thermal load on the surrounding TPC low.

Fig. 6 shows the results of the clinch process simulation with the inserts arranged on the punch side. Fields with a red background symbolize deformations or gaps (see red circles) between the parts to be joined which were classified as not acceptable.

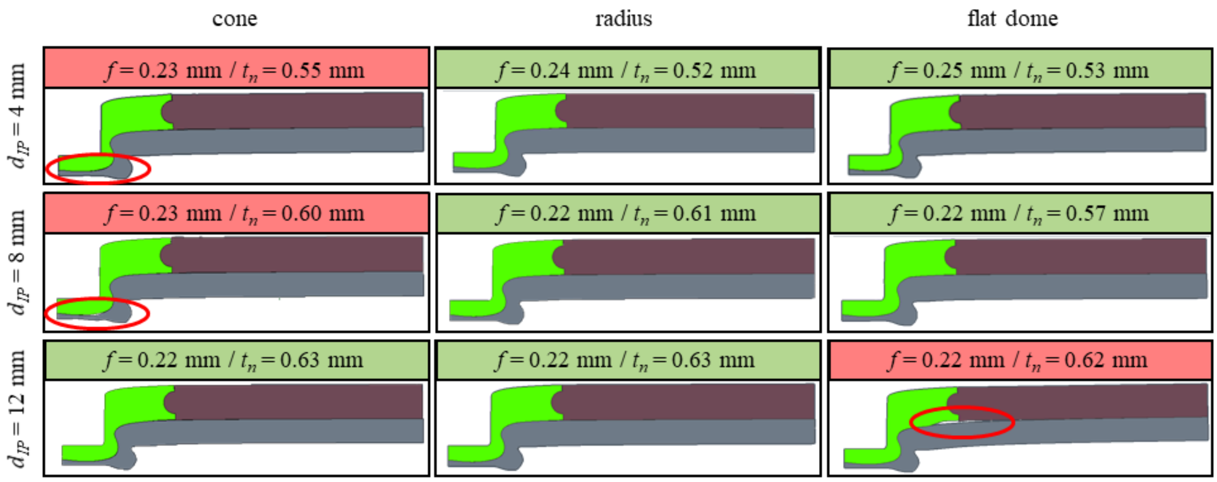


Figure 6: Results of clinching process simulation for insert arranged on the punch side varying the projection geometry and diameter.

Basically, it can be seen that, according to the numerical simulation, the weld projections are leveled as a result of the clinching process, with the exception of the flat dome variant with a diameter of 12 mm. Here it can be seen that the abrupt transition from the projection to the base of the insert lies so far outside the joining zone that the compressive forces applied on the process side in this area are not sufficient to level the projection completely. In the case of the variant with a cone, it can be seen that diameters of 4 mm as well as 8 mm result in a gap in the bottom area of the joint, which is to be classified as not acceptable. The quality-relevant parameters are almost unaffected by the projection geometry and reach the required minimum values for all variants.

The next step was to investigate the suitability of the different insert geometries for RSW. For this purpose, the maximum temperatures in the TPC were evaluated on the basis of selected process simulations in order to assess the thermal influence for the versatile inserts. The results together with the associated temperature distribution are shown in Fig. 7. Red fields indicate that a temperature of 160 °C has been exceeded, which is close to the melting temperature of the matrix.

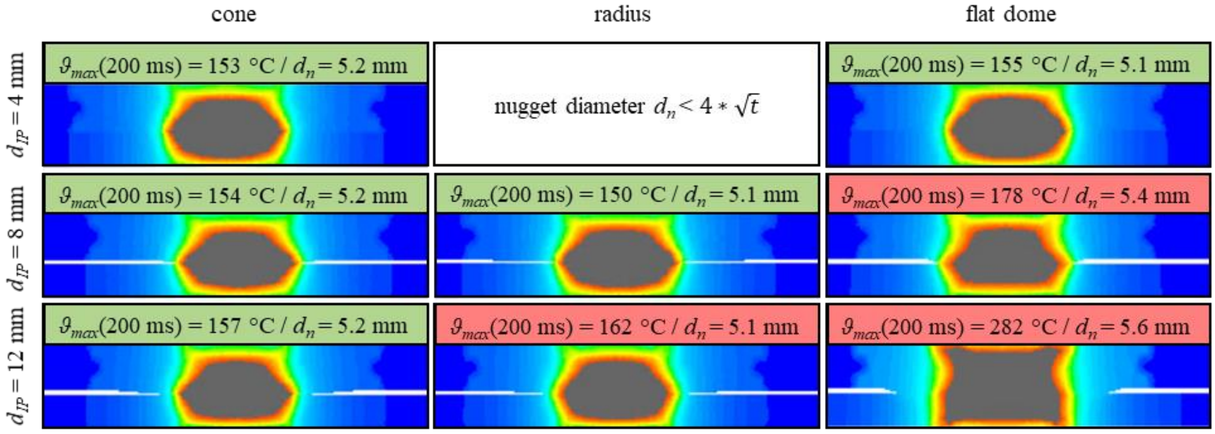


Figure 7: Simulatively determined temperature distributions for RSW of versatile inserts varying the projection geometry and diameter.

It can be seen that the maximum temperatures for the flat dome variant are comparatively high and also exceed the melting temperature of the matrix material. Due to the large insert volume, the cooling process also takes long, which is why the increased temperatures were classified as critical in this context. Furthermore, the joining results show that for a projection diameter of 8 mm and larger, a gap-free welding does not seem to be possible, regardless of the projection geometry. This can be attributed to the increasing volume of the projection with larger diameters. Accordingly, not the entire projection volume is melted during the welding process, which means that the gap is created by the unmelted outer area of the projection. For the radius variant with a diameter of 4 mm, numerical simulation shows that it is not possible to achieve welded joints that meet the requirements. This is only possible from a diameter of 6 mm, as additionally performed simulations have shown. At a diameter of 6 mm, the gap formation between the sheets is also marginal, which is why this variant was also classified as okay.

It can therefore be stated that, with regard to the welding process, a projection diameter d_{IP} of 4 mm is to be favored. However, since the clinch simulation showed a slight gap formation between the parts to be joined in the bottom area, the radius variant with a diameter of 6 mm was selected as a compromise solution to ensure clinched and welded joints that meet the quality requirements. In order to increase the head tensile strength of the joint, the head was also adapted to a countersunk head. This has no influence on the deformation behavior during clinching or the welding behavior. The final geometry of the developed versatile insert is shown in Fig. 8.

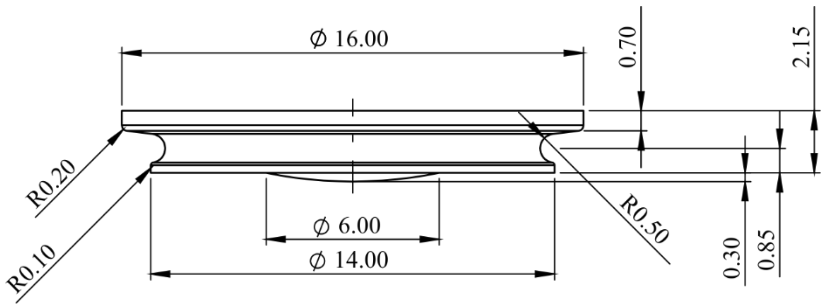


Figure 8: Design of the versatile insert (all dimensions in mm).

3.2 Analysis of the Joining zone

The quality of the joints was analyzed by micro-sections (Fig.9). It was shown that high-quality clinch joints can be achieved both with punch- and die-sided arrangement of the inserts. In addition, the same insert geometries can be used to create good quality joints with RSW.

Figure 9: Micrographs of clinched and welded joints using the same insert geometry: (a) Clinching with insert punch sided, (b) clinching with insert die sided and (c) RSW (1: GF-PP, 2: S235JR, 3: EN AW-6016 T4, 4: HC340LA) according to [30]

The measured quality relevant characteristics of the clinched joints are summarized in Table 3.

Position of the insert	Bottom thickness t_b	Undercut $(f_1+f_2)/2$	Neck thickness $(t_{n1}+t_{n2})/2$	Minimal t_b punch sided	Minimal t_b die sided
Punch sided	1.21 mm	0.18 mm	0.61 mm	0.89 mm	0.21 mm
Die sided	0.70 mm	0.24 mm	0.22 mm	0.22 mm	0.30 mm

Table 3: Measured dimensions of the clinched joints.

Based on the results for clinching, it can be seen that good quality joints are achieved for both joining directions. The same tools and joining parameters were used as for the joining process specific clinch inserts (cf. [6]). The quality-relevant parameters (in particular undercut and neck thickness) for the versatile inserts are less than those achieved when using the joining process specific clinch inserts. This can be explained by the fact that the versatile inserts have a larger overall height than the joining process specific clinch inserts, which is why the undercut is slightly reduced in the die-side aluminum part when arranged on the punch side while maintaining the required minimum base thickness. When the insert is arranged on the die side, the larger height of the insert mainly affects the neck thickness of the aluminum part. It should be noted at this point that specific adaptation of the tools can be expected to increase the joint quality. With regard to RSW, it can also be stated that joints meeting requirements can be achieved. The nugget diameter with 6 mm (Fig. 9c) is higher than $4 * \sqrt{t_{min}}$ (with t_{min} = 1.5 mm), which is a typical limit for RSW joints.

3.3 Mechanical testing

In addition, the joint strength was evaluated by single-lap shear tests for the different joining technologies. For clinch joints, the load-bearing capacity is higher with punch-sided (2.5 kN) than with die-sided (1.0 kN) arrangement of the insert (Fig.10). The load-bearing capacity of the welded joints is higher than that of clinched joints with a maximum shear load of over 5 kN. This demonstrates that high-quality joints can be achieved by using the innovative technology.

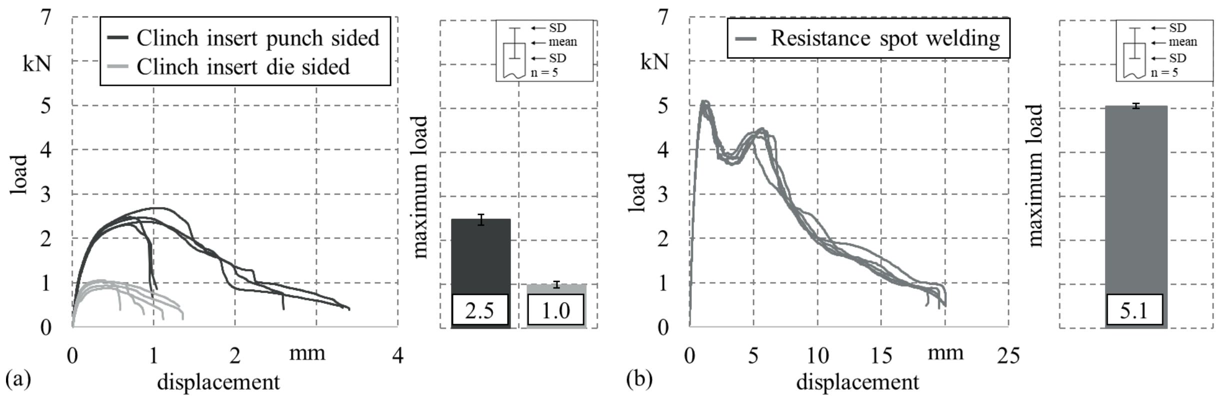


Figure 10: Results of single-lap shear tests under quasi-static load for (a) clinched joints with punch-sided and die-sided arrangement of the insert and (b) resistance spot welded joints.

Compared with the load-bearing capacities of joining process specific inserts (see [6] for clinching and [22] for RSW), it can be seen that for clinching these are lower for the versatile inserts for both joining directions. This is due to the lower quality-relevant characteristics of the joints, which can be attributed to the increased insert height. With regard to the failure behavior, the clinch joint also fails in the case of the versatile insert and the insert remains in the TPC, see Fig. 11 (a) and (b). For punch-sided arrangement, the clinch joint unbuttons, whereas for die sided arrangement a neck fracture occurs.

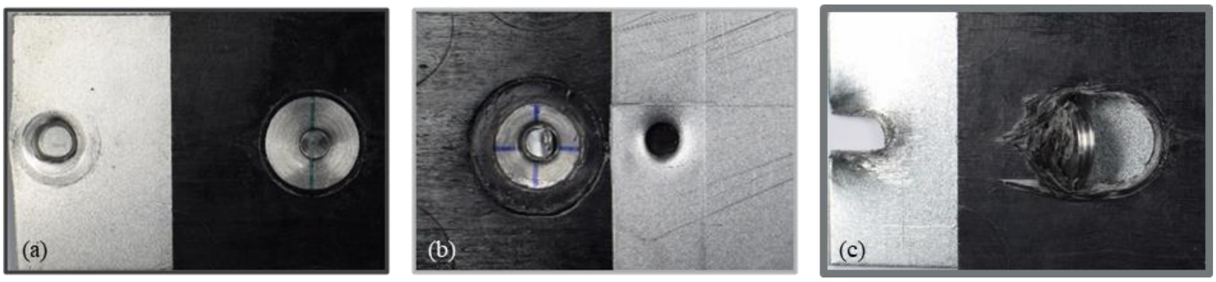


Figure 11: Failed single-lap shear specimen for (a) clinched joints with punch-sided arrangement of the insert, (b) die-sided arrangement of the insert and (c) RSW joints.

For RSW, on the other hand, the load bearing capacity of the joints is significantly increased compared to the joining process specific inserts, which is due to the larger diameter of the versatile inserts. In this case, the joints have failed by unbuttoning the insert from the TPC sheet, see Fig. 11 (c).

4 TECHNOLOGY DEMONSTRATION ON AN APPLICATION-RELATED STRUCTURE

In order to demonstrate the application potential of the technology, inserts were moulded into a three-dimensional structure (hat profile). The embedding of three inserts was performed simultaneously in the forming mould directly after the thermoforming of the TPC sheet [30]. Afterwards, two of these TPC profiles with embedded inserts were joined to a steel profile using clinching and RSW (Fig. 11). On the one hand, it was demonstrated that several inserts can be embedded into a TPC structure at the same time. On the other hand, it was shown that thermoforming of three-dimensional TPC structures and insert embedding can be combined in one mould.

Figure 11: Technology demonstrator with clinched and welded joints using inserts as joining interfaces.

5 CONCLUSIONS

TPC components can be clinched or welded to metal sheets by using embedded inserts as joining interfaces. A versatile insert geometry was developed that is suitable for both joining processes. The development of the inserts was supported by process simulations and took into account the specific requirements of both joining processes. It could be shown, that these inserts can be embedded in TPC during compression moulding in high quality and without fibre damage using a tapered pin tool. The quality of the final clinched and welded joints was analysed by microsections, confirming that the quality characteristics of the joints were achieved. In addition, single-lap shear tests demonstrated that good mechanical properties of the joints can be achieved. By means of a technology demonstrator, it was shown for the first time that several inserts can be integrated into TPC structures simultaneously with the regarded embedding technology. In addition, it was demonstrated that the technology can also be applied to three-dimensionally shaped structures. Thus, in the future, TPC components with inserts as joining interfaces can be produced without damaging the fibres and requiring no extra process step for insert embedding. Subsequently, the TPC component can be joined to metal structures using standard clinching or RSW machines and tools. For these reasons, the developed technology offers an excellent opportunity to integrate TPC parts into metal dominated multi-material systems.

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