Thermal Direct Joining of Hybrid Plastic Metal Components

Edmund Haberstroh*, Michael Sickert
Chair of Rubber Technology (LFK), RWTH Aachen University, Aachen, Germany

* Corresponding author. E-mail: haberstroh@LFK.RWTH-aachen.de
Received: 14 June 2014; Accepted: 10 July 2014; Published online: 31 July 2014
DOI: 10.14416/j.ijast.2014.07.002

Abstract
Joining technologies for multi-material design become more important. A new technology to combine the advantages of adhesive bonding and mechanical joining is the Thermal Direct Joining of plastic and metal. In this process the metal joining partner is heated up to temperatures above the melting temperature of the thermoplastic. If the joining temperature is reached, the thermoplastic is pressed under defined force to the heated metal. The thermoplastic melts close to its surface and wets the metal. Afterwards the joint is cooled under pressure. The advantages of Thermal Direct Joining are short cycle times, high bonding strengths and high reproducibility and process stability. Heating by a permanent heated stamp is investigated. The joining equipment was further developed to shorten cycle times, to raise reproducibility and to investigate on optimal process parameters. The results show that high tensile-shear strengths up to 25 MPa can be observed in short term overlap shear tests for the combinations of aluminium or steel with polyamide 6, polyamide 6 with 30 wt.-% short glass fibre reinforcement or thermoplastic fibre reinforced plastic with polyamide 6 matrix.

Keywords: *Plastic-metal-hybrids, Plastic-metal-joining, Thermal direct joining*

1 Introduction

Lightweight design cannot only be achieved by use of lightweight materials but also by combining different materials using their specific advantages. Especially the combination of plastics and metal has a high potential for lightweight designs. The plastic component can be used in areas where the mechanical loads are low and the stiffer metal component can be used to bear higher mechanical loads. Furthermore the plastic component can be used to integrate functionality into the hybrid component. To combine these very different materials joining technologies for the combination of plastics and metals need to be investigated.

Post-Mould-Assembly of plastics and metals is usually done via adhesive bonding or mechanically, e.g. bolting or riveting. Both techniques have specific disadvantages. Mechanical joining techniques lead in common to a discontinuous stress distribution. Adhesive bonding needs surface pre-treatment and time costly curing.

A new joining technology for joining plastics and metals is the Thermal Direct Joining, where the thermoplastic is used as kind of a hot melt itself. This technique is developed in the Cluster of Excellence “Integrative Production Technology for High-Wage Countries” where more than 20 institutes and over 100 scientists of material and production technology at RWTH Aachen University are cooperating in investigating the fundamentals of a sustainable production strategy. The aim of this scientific cooperation is to further develop the industrial production in high-wage countries in consideration of the challenges of a globalised production. The approach for new production strategies is an integrative production [1].

2 Plastic-Metal-Processing within the Cluster of Excellence “Integrative Production Technology”

One of the major issues of this Cluster of Excellence is the shortening of process chains for the production of hybrid plastic metal components. State of the art joining processes for plastics and metals can be divided into In-Mould Assembling processes and Post-Mould Assembling processes.

In In-Mould-Assembling processes the hybrid

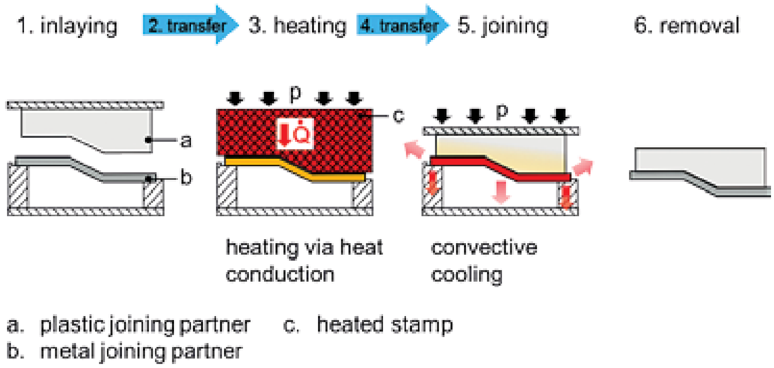

Figure 1: Process steps of Thermal Direct Joining [8].

part is usually produced by placing a shaped metal blank into an injection moulding machine. The plastic component is injected into the mould and the connection is achieved via form closure or an adhesive bond with the help of adhesion promoters. The advantages of this technique are a short process chain and the potential for cost savings. Disadvantages might occur with complex geometries and in terms of flexibility [2].

In Post-Moulding processes the hybrid components are usually manufactured with mechanical joining processes, such as riveting [3] or screwing, or with adhesive bonding. Both techniques have specific advantages and disadvantages. The mechanical joining processes show short cycle times and a high reproducibility but put additional weight to the components and create a punctual connection which leads to a discontinuous stress distribution. Adhesive bonding shows continues stress distributions but needs time costly curing after applying the glue [4].

To overcome the limitations of the shown In-Mould- and Post-Mould processes for the combination of plastics and metals, a new technology called Thermal Direct Joining was investigated in the framework of the cluster of excellence mentioned above [1].

3 Thermal Direct Joining

The Thermal Direct Joining is a joining technique for thermoplastics and metals. It uses the adhesive forces of a thermoplastic melt to metals to join both partners. The thermoplastic is used as an adhesive itself. The heating mechanism does not seem to influence the joint quality as the comparison between several investigations shows [5-8]. In this paper heating with a heat stamp is investigated. In the process the metal is heated to temperatures above the melting temperature of the thermoplastic joining partner and pressed under defined force to the thermoplastic which melts close to its surface due to heat conduction building adhesive forces to the metal. The process can be divided into six steps as depicted in Figure 1.

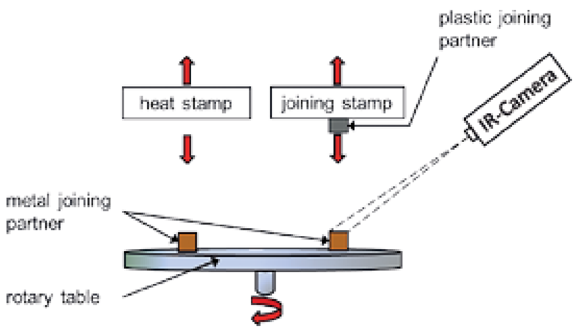

Figure 2: Principle of joining [8].

3.1 *Joining equipment*

In order to achieve high reproducibility and short cycle times a fully automated joining equipment was developed (Figure 2). To shorten cycle times, the heating and the joining process are separated. The transport of the metal between heating station and joining station is done with a rotary table which allows heating and joining to be done simultaneously. For the heating step a permanently heated stamp at temperatures higher than the deserved joining temperature is used. After the heating is finished the metal is transported to the joining station and the temperature of the joining

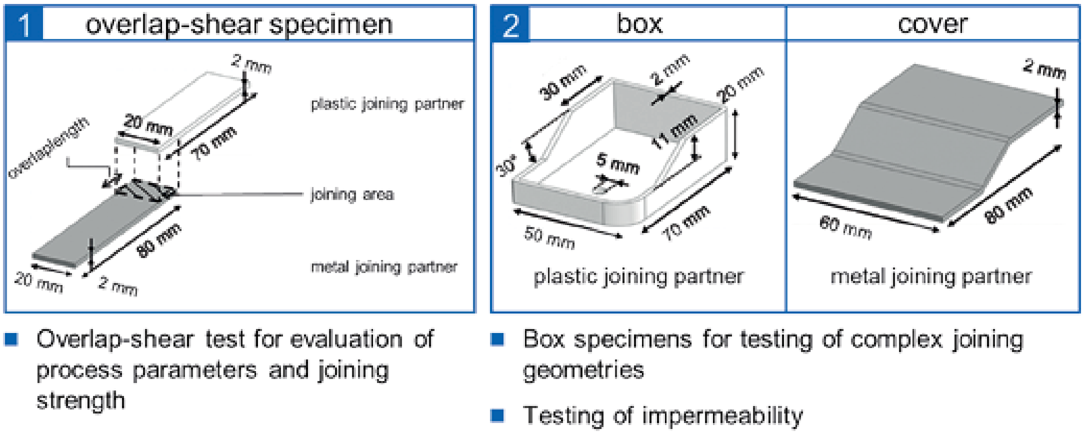

Figure 3: Investigated joining geometries [8].

area is monitored with an IR-Camera. The metal component cools down and if the joining temperature in the joining area is reached, the joining stamp with the thermoplastic is pressed to the metal.

The joining pressure can be varied during the joining process to enable a lower joining pressure after first contact between metal and plastic. The joining pressure should be raised again during consolidation to counter the thermal contraction of the thermoplastic. Compressed air is used to shorten cool down times. The cooling is switched on after a certain joining time.

3.2 *Investigated joining geometries and material combinations*

Two different part geometries have been investigated (Figure 3). The overlap-shear specimen is used to measure bond strength and for process optimisation. The box geometry is used to investigate on the joining of complex geometries and on the impermeability and the burst pressure of the joint.

The investigated materials for the metals are stainless steel 1.4301 and an aluminium alloy 3.3547. As plastic joining partners polyamide 6 (PA6), polyamide 6 with 30 wt.-% short glass fibre reinforcement (PA6GF30) and thermoplastic fibre reinforced plastic with polyamide 6 matrix (TP-FRP) are used. The TP-FRP has a glass fibre content of 47 vol.-% with a 0°/90° twill weave. The metal surfaces are joined untreated (ut) or sandblasted (sb). The sandblasting increases the surface roughness to enhance the mechanical adhesion. The overlap lengths for combinations with PA6 and PA6GF30 are defined to 5 mm and for combinations with TP-FRP 15 mm.

3.3 *Experimental results*

In a first step the influence of joining temperature on bond strength is investigated. The joining temperature has a high influence on resulting bond strengths. The optimal joining temperatures and resulting overlap-shear strengths are shown in Table 1.

Table 1: Optimal joining temperatures and resulting overlap-shear strengths for different combinations

Plastic	Metal	Pre-treatment	Joining temperature [°C]	Overlap-shear strength [MPa]
PA6	1.4301	ut	260	12
PA6	1.4301	sb	260	14
PA6	3.3547	sb	260	14
PA6GF30	1.4301	ut	320	18
PA6GF30	1.4301	sb	300	23
PA6GF30	3.3547	sb	340	21
TP-FRP	1.4301	ut	300	9
TP-FRP	1.4301	sb	330	19
TP-FRP	3.3547	sb	330	10

[*untreated (ut) / sandblasted (sb)*]

From several plastic joining processes it is known that a lowering of the joining pressure after the start of the joining process can lead to higher bond strengths. In the case here it is reasonable to start with a high joining pressure (p_1) which allows good heat conduction and wetting of the metal with thermoplastic

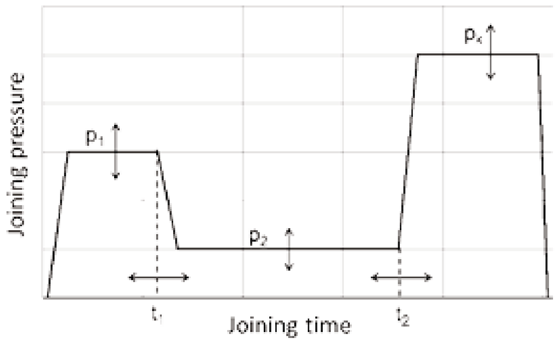

Figure 4: Typical course of the joining pressure profile for optimisation.

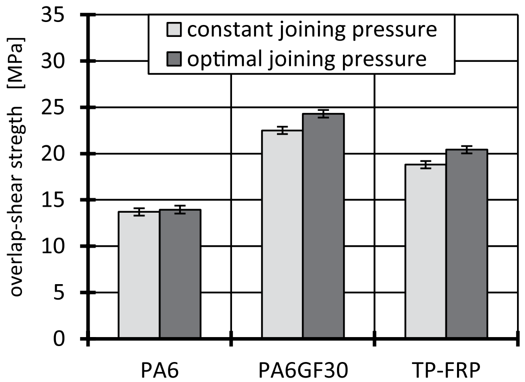

Figure 5: Overlap-shear strengths for different thermoplastics joined to sandblasted steel 1.4301.

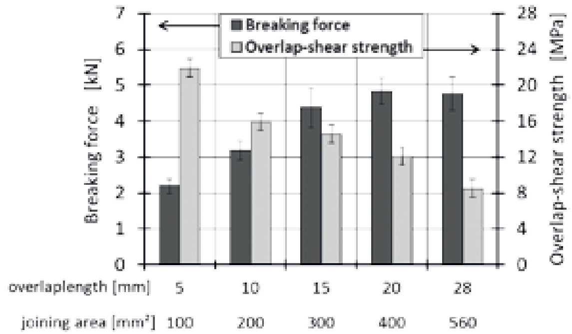

Figure 6: Breaking force and overlap-shear strengths for different overlap lengths.

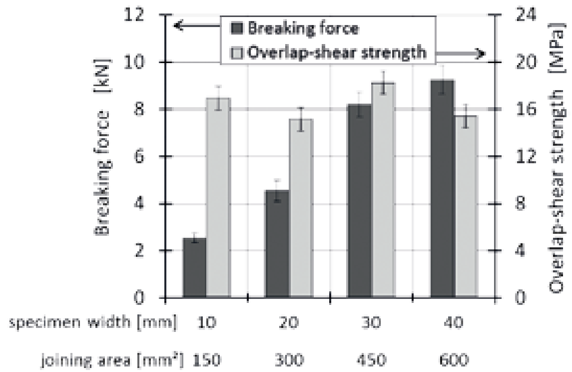

Figure 7: Breaking force and overlap-shear strengths for different specimen widths.

melt at the start. To prevent pressing out all melt to the welding beat the joining pressure is decreased (p_2) after a certain time (t_1). To counter the thermal contraction of the thermoplastic during the cooling phase the pressure is raised again (p_k at t_2) after the solidification of the melt to minimise residual stresses. An example for such a pressure profile is shown in Figure 4. During the optimisation values for the parameters p_1, p_2, p_k, t_1 and t_2 which lead to a maximal bond strength have to be found.

The resulting values for optimal pressure profiles can be found in Table 2.

Table 2: Optimal pressure profiles with sandblasted steel 1.4301

plastic	p_1 [bar]	p_2 [bar]	t_1 [s]	p_k [bar]	t_2 [s]
PA6	2	2	-	4	20
PA6GF30	2	1	5	4	20
TP-FRP	3	0,5	5	3	20

With optimised pressure profiles an increase of bond strengths for all thermoplastics can be observed. The increase is significant for PA6GF30 and TP-FRP with about 10% (see Figure 5). The increase in bond strength for the combination with PA6 is low because of the mostly cohesive failure of the PA6 specimens.

With optimised process parameters overlap joints with different overlap lengths and widths are produced. Figure 6 plots the resulting breaking force and overlap-shear strengths against different overlap lengths for the combination of TP-FRP and sandblasted steel 1.4301. It is obvious that with increasing overlap length the breaking force converges to a maximum. On the other hand the overlap-shear strengths decrease due to increasing joining area. For higher load transmission the overlap length cannot be increased.

Figure 7 depicts breaking force and overlap-shear strength versus different specimen widths with a constant overlap length of 15 mm for the combination

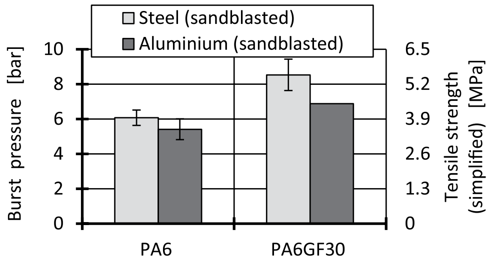

Figure 8: Burst pressure and simplified tensile strength of thermal joined box geometries.

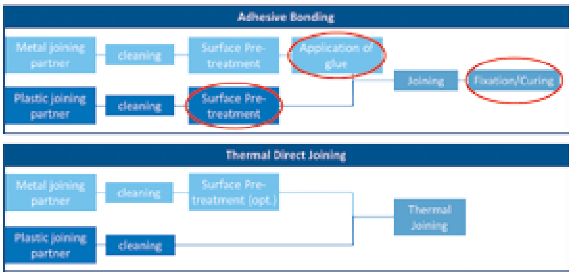

Figure 9: Comparison between the process chains of adhesive bonding and Thermal Direct Joining, acc. [1].

of TP-FRP and sandblasted steel 1.4301. The resulting breaking forces show nearly linear increase with increasing specimen width and the overlap-shear strengths are almost constant. Hence, a increase of joining width is suitable to increase the total bearable load. The shown results can be compared to the behaviour of adhesively bonded plastic metal joints.

The box geometry is used to investigate on the joining behaviour of complex geometries and on the impermeability of the joint. The joining parameters are set to the optimal parameters found for the overlap-shear specimens. The results show the joint is impermeable for liquid fluids at higher pressures, if the joint strength is higher than the resulting loads. To improve joint strengths, structuring of the metal surface is mandatory. With the help of the burst pressure a simplified tensile joint strength can be calculated according Equation (1) where σ_Z is the simplified tensile strength, pB the burst pressure, AP the projected area of the box and A_J the joining area. Figure 8 shows the burst pressure, at which the joined boxes fail and the resulting simplified tensile strengths.

$$\sigma_Z \approx \frac{p_B \cdot A_P}{A_J} \tag{1}$$

4. Conclusions and Outlook

With the joining process presented here, cycle times of less than one minute can be achieved after optimisation of the joining process. The joining process leads to reproducible joints of thermoplastics and metals with high bonding strengths. Compared to adhesive bonding the process chain for a plastic-metal joint is significantly shortened, see Figure 9.

To transmit higher loads an increase of the overlap length is not productive because the maximal transmittable loads raise with increasing overlap length to a maximum. This can also be observed for adhesively bonded parts. To transmit higher loads an increase of the joining width is feasible. With increasing joining width there is almost no effect of size.

Complex geometries can be joined and the joint can be seen as impermeable to liquids. Leakages can only occur if the resulting loads exceed the joint strength. To achieve high joint strengths, a sandblasting of the metal surface should be done.

In the future applications for the automotive industry are investigated at present time. Process parameters which are appropriate for online process control to predict joint strength in a production process need to be found. Another question is the long-term behaviour and the behaviour under different loads of the joint. First investigations show good behaviour under ageing conditions and in tensile creep tests, but further investigations are needed.

References

[1] C. Brecher, *Integrative Production Technology for High-Wage Countries*, Berlin, Heidelberg: Springer-Verlag, 2011.

[2] G. W. Ehrenstein, *Handbuch Kunststoff-Verbindungstechnik*, München: Carl Hanser Verlag, 2004.

[3] S. Amancia-Filho and J. F. Dos Santos, “Entwicklung des Reibnietens als neues Fügeverfahren für Kunststoff und Leichtbaulegierungen,” *Materialwissenschaft und Werkstofftechnik*,” vol. 39, pp. 799-805, Nov. 2008.

[4] G. Habenicht, *Kleben: Grundlagen, Technologien, Anwendungen*, 5. Auflage, Berlin, Heidelberg, New York: Springer-Verlag, 2009.

[5] P. Mitschang, R. Velthuis, S. Emrich, and M. Kopnarski, "Induction Heated Joining of Aluminum and Carbon Fiber Reinforced Nylon 66," *Journal of Thermoplastic Composite Materials*, vol. 22, pp. 767-801, June 2009.

[6] D. Flock, "Wärmeleitungsfügen hybrider Kunststoff-Metall-Verbindungen," PhD Thesis, RWTH Aachen University, 2011.

[7] J. Holtkamp, A. Roesner, and A. Gillner, "Advances in hybrid laser joining," *The International Journal of Advanced Manufacturing Technology*, vol. 47, pp. 923-930, Sept.-Dec. 2010.

[8] M. Sickert and E. Haberstroh, "Thermal Direct Joining for Hybrid Plastic Metal Structures," in *Proceedings Euro Hybrid Materials and Structures*, Stade, Germanyl, Apr. 10-11, 2014.