TOWARDS THERMOPLASTIC CARBON FIBER REINFORCED PLASTICS FOR THE AUTOMOTIVE INDUSTRY – THE NEED FOR AND POTENTIALS OF FUSION BONDING AND HYBRIDIZATION

Alex Schwingenschlögl[1], Nikhil Verghese[2], Philipp Bruckbauer[1], Stefan Ehard[1] and Klaus Drechsler[1]

[1] Institute for Carbon Composites, Faculty of Mechanical Engineering, Technische Universität München, Boltzmannstraße 15, 85748 Garching bei München, Germany
Email: schwingenschloegl@lcc.mw.tum.de, Web Page: http:// http://www.lcc.mw.tum.de
[2]Technology & Innovation, SABIC, Business Park 108, 6181 MA Elsloo, The Netherlands
Email: Nikhil.Verghese@SABIC.com, Web Page: http:// http://www.sabic.com/corporate/en/

Keywords: thermoplastic composites, composite joining, fusion bonding, thermoplastic welding

Abstract

Based on a literature review the need for and potential of fusion bonding / thermoplastic welding techniques within the automotive industry is described. Based on (i) a brief assessment of the current carbon fiber use and a prognosis of the future development and (ii) a short summary of the principles of the thermoplastic welding process, current available welding techniques are assessed for their suitability in an automotive environment, concluding that induction welding possess a high potential for structural welding applications while ultrasonic and rotational friction welding is favored for spot welding applications. Opportunities for hybrid material joining are highlighted exemplarily by (i) the functionalization of thermoset carbon fiber reinforced plastics by means of TP foils and (ii) hot bonding of TP layers to metallic surfaces by a modified thermoplastic automated fiber placement process.

The paper aims to provide the background and a basic starting point for the definition of further research efforts to be undertaken.

1. Introduction

This conference paper is largely based on a detailed literature review conducted by the Institute for Carbon Composites (LCC) / Technische Universität München (TUM) on behalf of SABIC [1]. The study included economic and technological topics in the field of joining composites and hybrids with a focus on thermoplastics and the automotive industry. Some of the data acquired are presented in this paper. In section 2. relevant trends in CFRP use within the automotive industry are highlighted, including prospects on further CFRP use, shares between thermoset and thermoplastic composites and the main obstacles within the automotive industry. Section 3. provides a very brief overview of the fusion bonding / thermoplastic welding process and its different techniques, followed by an assessment of the suitability and potentials of the different techniques on both a general (section 4.) and specific levels (section 5.). In the latter case two distinct applications will be reviewed: (i) "primary joints" for heavily load carrying, safety critical applications and (ii) "tertiary joints" fulfilling defined tasks without influencing the overall stiffness and crash performance of the vehicle.

The rising need for hybrid joining is covered by reviewing two promising techniques that are currently under investigation at the LCC: (i) the functionalization of thermoset (TS) CFRPs by means of TP foils enabling welding of TPs to TSs (section 6.) and (ii) the hot bonding of TP layers to metallic surfaces by a modified thermoplastic automated fiber placement (TP-AFP) process (section 7.).

Excerpt from ISBN 978-3-00-053387-7

2. (C)FRP, thermoplastics and the automotive industry – prospecting the future

Carbon fiber reinforced plastic (CFRP) use has made tremendous progress in the automotive industry over the last few years. In 2013 with the introduction of the BMW i3 we have seen the first carbon dominated vehicle design that is manufactured at an industrial level with almost 25000 vehicles manufactured in 2015 [2]. More recently, the new BMW 7-series has started production. Its body structure consisting of high strength steel, aluminum and magnesium alloys and a significant amount of CFRP reconfirms the forecasted trend towards multi-material design to achieve best weight reduction to cost relations, e.g. [3-9]. With around 60000 vehicles [10] to be manufactured annually, resulting in some hundred thousand CFRP parts per year, CFRP production rises to new heights.

Apart from BMW, no OEM is currently using or planning to use CFRP in higher volume production, though “all” of them are investing in research and development and some team up strategically with carbon fiber suppliers [12]: Examples of these are the partnerships between BMW and SGL, General Motors and Toho Tenax, Ford and DowAksa and Jaguar and Cytec.

On the other hand, even BMWs enthusiasm for CFRP seems to be limited. The new rear wheel drive cluster architecture “CLAR”, formerly known as “35up”, which will be the common architecture for all BMW models from the 3-series upwards, does not enforce the use of CFRP in the body design exclusively. Whilst until now, no official statement by BMW is available, there are strong indications in different media that the new 3-series (start of production (SOP) in 2018) will not contain any CFRP and the 5-series (SOP 2016) to a much lesser extent if any. Most likely the use of CFRP will be limited to the upper end of the CLAR architecture: the 5GT-, 6-, X5-, X6- and X7-series, all starting production before 2019. The next BMW i-model (SOP ~2020) is also reported not to use CFRP as the dominant material anymore, though the share shall be significant. BMWs technological strategy seems to shift its focus from sustainable mobility, including lightweight construction, towards connectivity and autonomous driving [11].

From a more general perspective, enthusiasm concerning composite use in the automotive industry has slowed down, while – at the same time – acceptance has risen. In the short term, a rise in carbon fiber use is secured and there is a solid interest in composites throughout industry. However the tremendous enhancements in process robustness, reductions in process and material costs and cycle time throughout the entire process chain from ply stacking to final assembly, that have been made so far, are obviously not sufficient to meet customer (cost) requirements. In the long run CFRP will only be competitive to other materials if the performance to weight reduction ratio (measured in €/kg-saved) will increase further. Table 1 highlights “rough” expectations as given by Heuss et al [4].

Table 1. Allowable lightweight costs depending on car segment based on [4].

Powertrain	Internal combustion engine	Hybrid / range extended electric vehicle	Battery electric vehicle
Car segment			
Luxury	8-20 €/kg saved		
Upper medium & Executive	5-14 €/kg saved		
Medium / Small	~ 3€/kg saved		

Researchers, engineers and business strategists see the use of thermoplastic (TP) composites as one of the most promising approaches to reach cost goals [12-17]. BMW’s CFRP technology roadmap as presented in 2014 [13] is focused on maximum cost saving potential within high scale production by the use of thermoplastic CFRP. Current research and development activities of other major market players point in the same direction. The potentials seen in the use of thermoplastic CFRP are manifold: a further decrease in cycle time bringing it down from several minutes to a single minute or below, reduction of manufacturing induced material waste and easier reuse / recycling of this waste and at end

Excerpt from ISBN 978-3-00-053387-7

of life, lightweight potential by a more integral design and combination with existing thermoplastic processes, e.g. back injection molding, a higher level of automation, to name just a few. Likewise, it has been pointed out, that thermoplastic composites enable welding, which is a fast process, requires less surface preparation and cleanliness than adhesive bonding, may be easier integrated in the "standard" automotive assembly process and as a result will reduce manufacturing costs, time to manufacture and inventory.

3. The basic principle of thermoplastic welding / fusion bonding and its techniques

Fusion bonding of TP polymers of the same type needs intermolecular diffusion and chain entanglement across the welding interface. The process consists of two phenomena: intimate contact and autohesion / healing. The former requires that intimate physical contact is achieved between the two surfaces to be joined. As surfaces are never perfectly smooth the surfaces asperities must be deformed. Process parameters influencing intimate contact are applied pressure, temperature, time, surface roughness and type of material, especially its viscosity and density. Autohesion / healing describes the phenomena that once the interfaces conform to each other, they heal together by diffusion and interpenetration of polymer chains and chain entanglements across the interface. Under ideal conditions at complete healing, the interface essentially becomes indistinguishable from the bulk material. This process is thermally activated and time dependent (see Figure 1). The minimum temperature (T_{min}) required for healing is depending on the type of polymer. For amorphous thermoplastics it is sufficient to pass glass transition temperature while for semi-crystalline thermoplastics melting temperature must be exceeded. Given sufficient time for healing, consolidation (cooling below T_{min}) results in a solid weld [18].

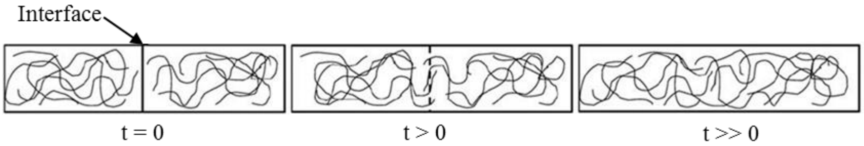

Figure 1. Molecular healing of the interface over time. Figure based on Grewell and Benatar [18]

The strength of a welded thermoplastic joint may reach the strength of the thermoplastic base material and is highly dependent on process parameters (pressure, temperature and time) and resultant weld quality [19]. Welding of thermoplastic FRPs – apart of giving rise to some processing issues, like uneven heating, delamination and distortion of the laminates – results in the general issue that the weld strength is far below the strength of the composite. Just like in adhesive bonding loads need to be transferred in shear and sufficient "bond area" must be provided to allow load transfer across the weld. The interaction between process, weld quality and mechanical performance seem to be aggravated. For example Ageorges, Ye and Hou [19] report single lap shear data ranging from 5 to 50 MPa depending on process, parameters, aid- and processing materials for the same base Material (APC-2 Peek).

In general thermoplastic welding techniques are classified by heat generation principle as summarized in Table 2. The wide variety of TP welding techniques preludes discussing each of them in every detail. For more details please refer to the more detailed reviews provided in [18-22]. Additionally Table 2 provides some references for specific techniques.

Excerpt from ISBN 978-3-00-053387-7

Table 2. TP-welding techniques classified by heat generation principle

Heat generation principle	*Heat conduction*	*Frictional heat*	*Electric conductive*
Welding techniques	Conduction (hot tool) welding [23]	Friction welding [28,29]	Resistance Welding [31-33]
	Convection (hot gas) welding		
	Radiation welding	Ultrasonic welding [29]	Induction welding [34-38]
	Laser Through Transmission Welding (TTW) [24-27]		

4. General assessment of TP welding techniques by inherent process features and restrictions

Though all TP welding techniques rely on the same principle of healing and consolidation and thereby share some identical potentials, the techniques differ drastically in their inherent processing features, subsequent restriction and eventually their potential use. A summary of the following discussion is provided in Table 3.

Melting the surface of the adherents can be achieved via heat conduction. Hot tool welding and some radiation based techniques, like laser welding and infrared welding, require that heating is accomplished prior positioning the two adherents in their final position. This may limit their suitability in three ways. First of all the loss in temperature in between heating and pressure application in final position needs to be accounted for. The loss is higher for composites than for unreinforced thermoplastics due to the higher thermal conductivity of the composites. The usable process window either in time or in temperature is tighter. Second, the maximum size and complexity of the part and the weld is limited by concurrent heat up all over the part and the loss of stability during heat up. Typically these techniques are limited to butt welds and “areal” welds of limited size, making them less suitable for structural welds. Hot tool welding adds some more negative features: The polymer may stick to its surface resulting in a potential loss in quality over time and higher maintenance efforts. It is also rather costly in terms of energy consumption.

Laser welding may also be performed in final position. Unfortunately when doing so, the welding geometry is limited to butt welds of the front edges of rather thin adherents, making it unsuitable for any structural weld with FRPs.

Microwave welding as another heat conduction based method has entirely different characteristics: Most commonly a thin layer of electromagnetic absorbent material is placed between the joint elements to assure highest heat up rates in the joint area. Positioning in final position is taking place prior to heat up and weld size (length, width, area) is only limited by the size of the implant and the size of the microwave oven. Unfortunately carbon fibers provide a shielding effect by reflection (reducing the overall heat up) and absorption (leading to a heat up of the outermost plies). Thereby weave style, lay-up orientation are becoming influencing factors on the process and metal inlays may affect bond strength and cause corrosion issues. Subvariants without an extra absorbent layer and continuous joining (allowing for butt welding only) exist [20]. Over all microwave welding does not seem attractive for high scale manufacturing.

A special case is laser through transmission welding (TTW): In this case, the laser beam is transmitted through a transparent / transmissive layer. The absorption and thereby the heat generation takes place at the top surface of the absorbing layer allowing for heat concentration at the joint interface. In this standard configuration it allows to weld a transmissive component onto a composite part. Thereby it may replace spot welding techniques in some cases. It may also be used to join two composite components by using a transmissive welding aid material. Standard weld line geometries as known

Excerpt from ISBN 978-3-00-053387-7

from metal welding are possible (see Figure 2). Although the maximum width of the fillet is restricted and no wider overlaps / bond width may be accomplished, the process allows for continuous bond lines of “endless” length, which may result in sufficient bond area even for structural applications. Large and complex parts may be joined by using standard industry robots. A further positive aspect is that heat up can be generated very locally generating only a rather small heat affected zone. On the opposite side granting entire filling of the fillet which requires a high degree of melting of the welding material without local overheat damage of absorbent base material is not an easy task and may require special weld aid material geometries.

Table 3. Assessment of TP-welding techniques by inherent process features and restrictions

Welding technique	*Process features*		*Restrictions*		
	Processing sequence	*Additive required*	*Type of weld*	*Size of weld / adherent*	*Adhered geometry*
Hot tool	HPP	N	BW (AW)	S	Me
Hot gas	PPH	Y, WM	BW	H	Co
Radiation / Infrared	HPP	N	BW (AW)	S	Me
Radiation / Laser	HPP (PPH, for BW only)	N	BW (AW, LW)	S,(H, LWC-WR)	Me
Radiation / Microwave	PPH	Y, APM	BW, AW	M	Co
TTW	PPH	(N, transmissive adherent) Y, APM	(SW), BW, AW, LW	H, LW-WR	Co
Friction welding	PPH	N	BW, AW, SW	S, SW	≤ Si; ≤ Co for spin welding
US; energy directors	PPH	N	BW, SW	S, SW	Me
US; sonotrode	PPH	N	SW, (AW)	S, SW	Co
Resistance	PPH	Y, APM	AW, LW	H, LW-NWR	Co
Induction	PPH	Y, APM in general; N for CFRP	AW, LW	H, LW-NWR	Co

Abbreviations: HPP = heating prior positioning; PPH = positioning prior heating; Y = yes; N = no, WM = welding material; APM = auxiliary process material; BW = butt weld; AW = “areal” weld of surfaces; LW = “longitudinal” weld = continuous weld line in one direction; S = small; M = medium; H = huge; LW-WR = continuous longitudinal weld, width restricted, LW-NWR = not width restricted; Si = simple; Me = medium; Co = complex

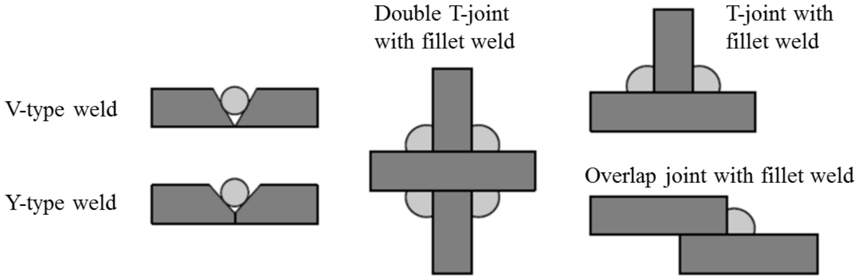

Figure 2. Welding geometries for TTW welding using a transmissive welding aid material

Excerpt from ISBN 978-3-00-053387-7

Frictional heat can be generated by a macroscopic movement (frictional welding) in linear (linear vibration welding) or rotational direction (rotational welding or spin welding). Linear vibration welding is limited to flat parts or at least flat joint areas attaching one adherent on top of the fiber plane of the other adherent (overlap configuration). The size of the welds is limited. Even in that configuration the potential of distorted and broken fibers is high. A self-reinforcing effect by local displacement of the matrix and a resultant higher fiber volume fraction was reported [20]. The size restrictions for spin welding are even higher. Due to the rotational movement, maximum heat generation and melting is taking place at the outer radii, making it a well-suited technique for butt splicing small diameter rotational parts and hollow circular parts of non-reinforced plastics and spot welding small rotational parts on top of plane of a (locally) flat adherent, including FRPs. Again, even in that configuration, distortion and brakeage of fibers is an issue [19]. Both techniques allow for low cycle times (per weld) and are insensitive to surface preparation.

In ultrasonic welding the frictional heat is generated by subjecting the joint members to ultrasonic vibrations perpendicular to the contact area under pressure. The coupling may be enforced by energy directors or sonotrodes. In the former case the fact that vibrational energy concentrates around surface asperities dissipating heat is used by introducing “man-made” asperities: the energy directors. In the latter case sonotrodes either are penetrating the upper part entirely (“pin-sonotrodes”) or are touching the surface of the upper adherent (“flat” or “spherical” sonotrodes).

In induction welding the standard process is to generate heat around a ferromagnetic implant or susceptor between the adherents by positioning in a high radio-frequency electromagnetic field. The heating itself is dominated by “Joule-losses” [35], dielectric losses of the polymer itself playing only a minor role. The implant must conform to the shape of the bond area and can be provided as foil like tape or particles molded into the polymer. For CFRPs the use of an implant may be neglected if the fibers form closed electrical current loops as it is the case for braidings, fabrics and multi-axial non-crimp fabric. It is not applicable to uni-directional tape laminates with lay-up in one direction, which is hardly ever the case [35]. Each of the techniques has its benefits and shortcomings: using an implant may result in extra costs for the material and its application and with CFRP may provoke corrosion issues. Alternatively working without implants results in heating of the material in bulk, which may need active surface cooling, to restrict melting to the joint interface only. Induction welding can be applied as discontinuous process, heating the entire weld zone all over the part at once, or as continuous process of local heating and local consolidation as depicted in Figure 3. In the latter case the consolidation pressure is provided by consolidation rolls, cooling by actively cooled rolls [39] or separate air stream [36]. Continuous induction welding seems a very attractive joining technique if non-length restricted welded joints are necessary. In comparison to TTW there is no width restriction of the weld line making the process more suitable for heavily loaded structures. Automation, system integration, rapidness of process and capital investment are better or equivalent to it.

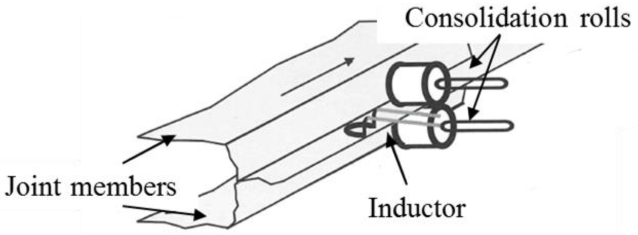

Figure 3. The principle set-up of the continuous induction welding process according to [39]

Excerpt from ISBN 978-3-00-053387-7

Resistance welding uses an electrically resistive element or implant between the joint elements. By applying an electrical current the implant is heated and the surrounding polymer at the interface is melted. Reconsolidation under pressure results in a solid weld. Implants may be made from metal mesh, carbon strips or other conductive materials. Subvariants differ in terms of sequence: single step resistance welding heats the entire weld line at once, while multi-step or sequential resistance welding is heating portions of the weld line sequentially on after another. The latter is said to provide advantages in terms of heat distribution (locally more uniform, controllable heating) and subsequent quality and performance at reduced energy needs. Energy consumption may also be reduced by using impulsive resistance welding rather than continuous power resistance welding: Less energy is consumed providing the energy by intense pulses. The advantages of resistance welding include being a simple, clean and robust process that has the proven ability to result in high quality bonds. In its sequential variant the process is able to manufacture non-length and width restricted joints on complex parts like induction welding. It is argued, that by the implant remaining in the final part disassembly is eased giving some benefits in terms of repair and recycling [39]. In any other respect the inlay is a significant backdraft. It adds material and process costs, slows manufacturing / cycle time and may need additional corrosion prevention if a metallic inlay is used with CFRP. Over all the process is slower than laser or induction welding, though reasonable cycle times should be met if sufficient areas are heated at the same time.

5. Assessment of TP welding techniques for different applications

Based on the general assessment provided, two specific applications on “carbon heavy” vehicle designs currently accomplished by adhesive bonding are discussed: (i) spot-welding of tertiary joints and (ii) large area welding of primary joints.

(i) Spot-welding of tertiary (pin) joints:
The definition within this paper is, that any joint that is neither safety critical in terms of crash performance nor influences the overall stiffness of the vehicle will be addressed as a tertiary joint. Anyhow, tertiary joints do have specific tasks, that may have strict technical requirements and influence the quality impression of the vehicle, e.g. by carrying the surface panels. A good example are the so-called onserts, –hybrid pins, consisting of a metallic threaded bolt and a polymer base – to attach add-on parts onto the CFRP body structure as depicted in Figure 4. They are excessively used on the BMW i3. Currently these onserts are adhesively bonded by a one component, light sensitive adhesive that cures within four seconds after being activated by LED lamps [40].

(ii) Large area welding of primary joints:
By contrast a primary joint is defined as any joint that is playing a dominant role in terms of crash performance and stiffness. The adhesively bonded body structure of the BMW i3 and i8 are good examples. The body consist of a multitude of separate body panels. Exemplarily see Figure 4. Currently the joining is accomplished by adhesive joining with a polyurethane adhesive. However, no official numbers are available on cycle times we expect that adhesive application and curing to allow for further handling are both in the lower single digit minute time span.

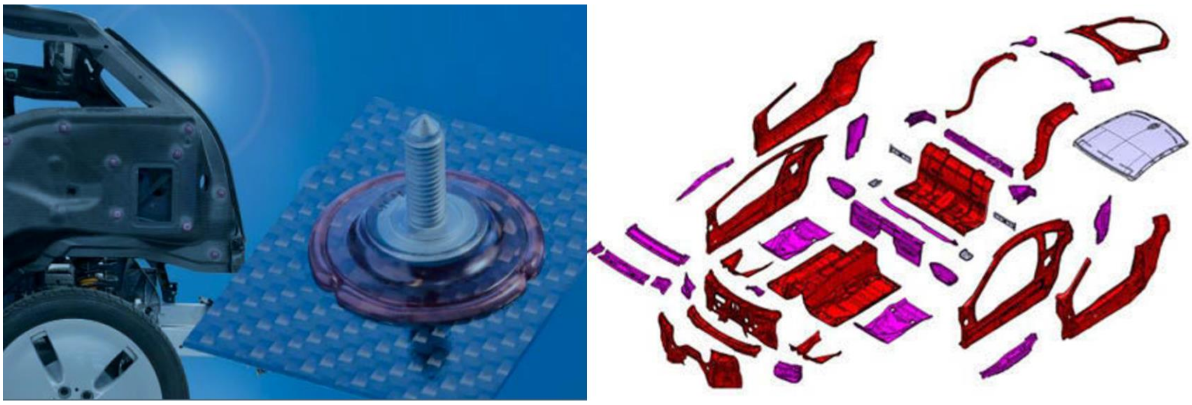

Figure 4. Adhesively bonded onserts (left) [40] and CFRP body panels of a BMW i8 to be adhesively bonded (right) [41]

Excerpt from ISBN 978-3-00-053387-7

For both applications an assessment of the most suitable thermoplastic welding process – given that a similar thermoplastic structure would exist – was performed. Table 4 highlights the results.
Concerning spot welding of tertiary joints rotational friction welding and ultrasonic welding with energy directors seem equally interesting for further research and development work. Both offer short cycle times at reasonable costs without major disadvantages. The local fiber distortion and breakage at the interface seems acceptable in most applications and may be reduced / prohibited by adding some extra thermoplastic material at the surface. Through transmission welding provokes some constraints like transmissive base material of the onsert / pin and extra investment costs without adding value. Using ultrasonic welding with sonotrodes from a more general level seems very promising. In the specific case for pin application it is not really applicable though: welding may not be performed centrally as the pin is in the way and therefore would require a broader base and several spotwelds.

Table 4. Assessment of TP welding techniques for spot welding of tertiary joints and welding of primary joints

Application	*Welding techniques*	*Process performance*		*Costs*	
		Cycle time	*Process robustness / applicability*	*Investment*	*Cost per part*
Spot-welding of tertiary joints	Rotational friction	++	+	+	+
	TTW	+	0	--	0
	US / energy directors	++	+	+	+
	US / sonotrode	++	--	+	++
Welding of primary joints	TTW	++	-	-	+
	Induction (without implant)	++	+	0	++
	Resistance	- … +	0	0	--

++ = very good … -- = very bad performance

Concerning the welding of continuous primary joints induction welding is favored for further research and development as outstanding low cycle times and costs per part seem possible and no major backdraft is expected. Extensive work on machine and system set-up and process parameters seems necessary to limit the heat up to the welding zone / prevent heating of the material in bulk.
From a quality point of view resistance welding is expected to be equally well suited, but the extra costs for implants and their application are a major disadvantage. For through transmission welding the somewhat higher investment costs are not an issue in terms of higher scale production, but the limited width of the weld line and thereby limited strength will either prohibit its use or impede the designing appropriate welds.

6. Fusion bonding of thermoset composites by means of a thermoplastic functional layer – a novel approach

A promising approach to use fusion bonding techniques for thermoset CFRP is to add a thermoplastic surfacing film to the thermoset composite. During composite manufacturing a thermoplastic surfacing film is co-cured to a thermoset composite to make the thermoset CFRP material weldable. This approach provides new options of integral designs and the use of various rapid and robust fusion bonding methods in comparison with adhesive bonding or mechanical fastening. Furthermore, new levels of flexibility in the repair and replacement of CFRP components can be achieved.

Excerpt from ISBN 978-3-00-053387-7

A joint between thermoplastic (TP) and thermoset (TS) composite consists of an interphase between TP and TS and between TP and TP created by a subsequent fusion bonding process. As a strong TP-TS interphase is essential for every conceivable joining technology it will be explained on more detail in the following. Further general information can be found in a review by Deng et al. [42].

Some thermoplastics such as polyethersulfone (PES), polysulfone (PSU) and polyetherimide (PEI) are known to be soluble in the uncured resins and have been used to toughen epoxy resins without decreasing other desirable mechanical properties [43-46]. If such a suitable combination of thermoset and thermoplastic surfacing medium is used, an inter-diffusion of macromolecular chains of both materials takes place. As the resin cures, a strong interfacial bonding between the thermoplastic and the epoxy is formed by a reaction induced phase separation mechanism [47] and a gradual interphase develops as shown in Figure 5.

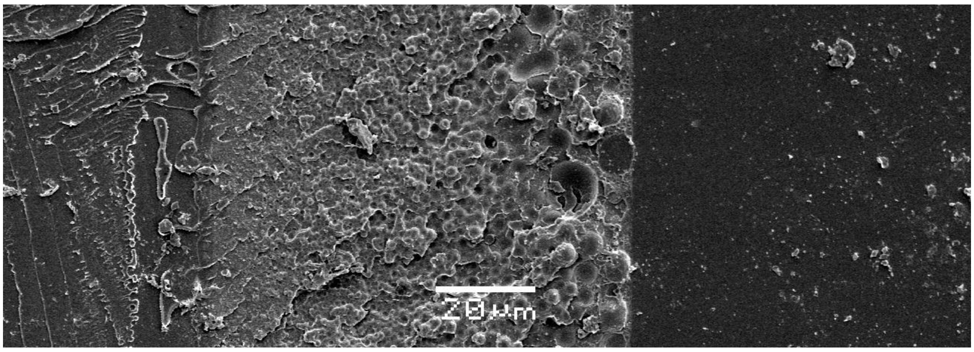

Figure 5. Gradual interphase between PES (left) and epoxy resin based on tetraglycidyl methylene dianiline and aromatic hardeners (right).

The concept of joining thermoset CFRP by means of thermoplastic-thermoset interphases has been shown to reach good mechanical performance comparable or even higher than the baseline of structural monolithic parts or fusion bonded samples [48-50]. However, the structure of the resulting interface is dependent on parameters of the curing process such as time, temperature and heating rates. Up to date most of the studies were performed with comparable slow curing resin systems and rather expensive high performance thermoplastics. Regarding the requirements in automotive industry such as costs and short cycle times, cheaper thermoplastics in combinations with fast curing resins systems must be applied. Furthermore suitable use cases have to be identified.

Current research is focused on the suitability for non-structural joints, e.g. clips and brackets, and structural joints between whole composites parts with thermoplastic and thermoset matrix respectively. Further thermoplastics, e.g. acrylonitrile butadiene styrene (ABS), have been proven to be compatible with the epoxy resins applied. Nevertheless, the reduced time scale for interphase formation in fast curing resin systems is still an issue to be covered even if first tests show promising results.

The thermoplastic surfacing technique provides a straightforward assembly process and does not compromise the mechanical performance of the welded joints. Furthermore, widespread applications of this approach are possible as for example selective thermoplastic layers in thermoset based composites for dismantling or easier recycling of structures.

7. A special case: Fusion bonding of thermoplastic layers to metallic surfaces by a modified Thermoplastic Automated Fiber Placement process

Automated Fiber Placement of continuous fiber reinforced thermoplastic tapes (TP-AFP) is a promising manufacturing technology for the production of high-performance composite structures.

Excerpt from ISBN 978-3-00-053387-7

Using TP-AFP, composite parts are manufactured according to the mechanical load paths of the structure with a high degree of automation. Recent developments demonstrated the capability of an in situ consolidation of the laminate during lay-up [51-53]. Expensive manual labor, costs for consumables and process time compared to a thermoset autoclave curing cycle can be reduced. Besides the constant ongoing research on manufacturing thermoplastic composites, joining of CFRP and metal substrates by TP-AFP is currently under investigation. [54, 55] The advantage of using TP-AFP for joining CFRP and metal is the combination of the joining step and the laminate consolidation of unidirectional tape materials.

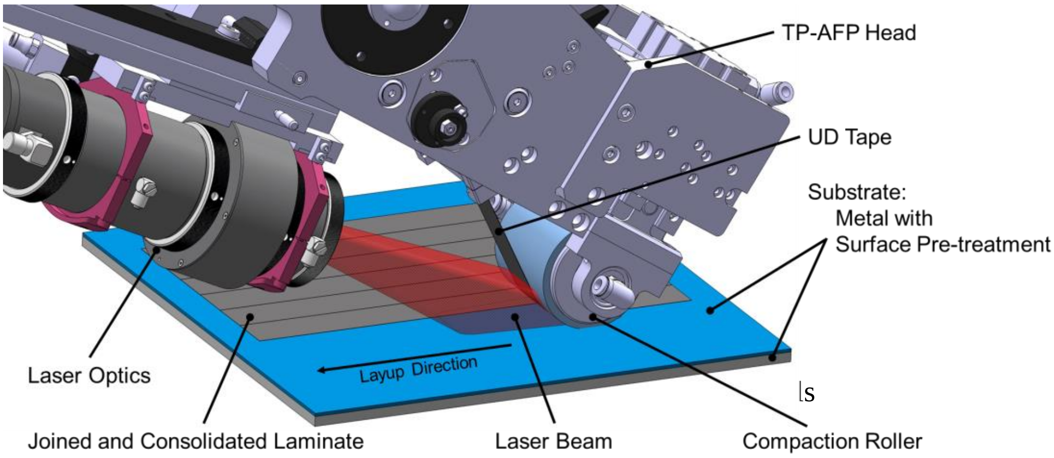

Figure 6. Modified TP-AFP process for joining CFRP

When joining CFRP and metal by TP-AFP endless-fiber reinforced tape material is fed through a fiber placement head to the compaction roller and is positioned on top of the pre-treated metal. By laser radiation, the incoming tape material and the metal substrate are heated to the melting temperature of the composite's matrix. During compaction by the roller, the thermoplastic matrix solidifies and the joint is generated. A modified fiber placement head, derived from tape winding technology is used to manufacture hybrid structures. Permanent data recording of the process parameters ensures an online quality control of the joining process. After joining, the in situ consolidation of the remaining plies is realized by a closed loop control of laser power and laserspot distribution. According to the measured temperature in the substrate and incoming tape material, both is adjusted to stay within the ideal process window.

First studies have shown that by TP-AFP joint strength comparable to state-of-the-art joining technologies can be realized [54]. Joining material combinations used in aerospace applications, like CF/PEEK and titanium [56], and joining of automotive material systems, like CF/PA6 and aluminum [55], has been successfully demonstrated. Depending on the material combination, surface pre-treatment of the metal, analysis of the optical behavior of the joining partners and finally process parameter optimization for joining and laminate lay-up are key aspects for a durable joint and currently under investigation.

In relation to other fusion bonding technologies challenges regarding equipment size, e.g. clamping devices, effectors etc. can be overcome due to the flexibility of the fiber placement head. This kind of additive manufacturing of the CFRP structure on the pre-treated metal surface provides more flexibility with respect to component size or integration in existing production lines. There is only a local heat input, limited to the laser spot size when joining CFRP and metal in the TP-AFP process, reducing the heat affected zone and therefore warpage due to the mismatch in thermal expansion of CFRP and metal after cooling. Joining of endless-fiber reinforced thermoplastic tape materials and metals by TP-AFP provides a smart process chain at a high degree of automation.

Excerpt from ISBN 978-3-00-053387-7

7. Conclusion

Based on the literature review performed the major conclusions drawn are:

(i) The solid interest of the automotive industry in FRPs in general, and CFRPs in particular, provides the playground for scientists, technicians and engineers to make composites a success story in lightweight, multi-material vehicle design. This potential will only come true if the costs for lightweighting by means of FRPs continue to decrease drastically.

(ii) Thermoplastic welding / Fusion bonding technologies are considered to be both suitable and enabling at the same time: While TPs are considered necessary for further cost and cycle time reduction and thereby create a need for TP joining technologies, TP welding has the potential to amplify that gain.

(iii) A wide variety of TP welding techniques are at hand and some techniques seem especially promising in automotive manufacturing, including induction welding for primary joints and spin welding and ultrasonic welding for spotwelding applications. Many other welding techniques may be equally suited depending on application. Anyhow, significant research and development efforts need to be made.

(iv) The ability to join hybrid parts and multi-material vehicles will be paramount. Enabling fusion bonding / TP welding of TS by means of adding a functional TP layer has the potential to be faster, cheaper, more robust and less demanding qualitywise than adhesive bonding. Likewise in-situ, net-shape consolidation of CFRPs with metals shows positive aspects in terms of minimizing material waste and number of process steps. Again, further research and development work is necessary.

Acknowledgments

The authors gratefully acknowledge the support of SABIC by funding the study. The corresponding author would like to thank Nikhil Verghese, Joris Wismans, Warden Schijve and Gino Francato (SABIC) for intense discussions and Elisabeth Ladstätter, Veronika Radlmaier, Chris Lemke and Swen Zaremba (Institute for Carbon Composites) and Andrea Hohmann and Jakob Wölling (Project Group Functional Lightweight Design / Fraunhofer Institute for Chemical Technology) for support and co-authorship during the preparation of the study.

References

[1] A. Schwingenschlögl, E. Ladstätter. *Joining of Composite and Hybrid Materials with Focus on Thermoplastic Materials and the Automotive Industry*. Institute for Carbon Composites, TUM, 2014.

[2] BMW Group. *BMW Group achieves fifth consecutive record sales year*. Press release. 1/11/2016, available online at https://www.press.bmwgroup.com/global/article/detail/T0249765EN/bmw-group-achieves-fifth-consecutive-record-sales-year, checked on 4/1/2016.

[3] J. Dau, C. Lauter, U. Damerow, W. Homberg, T. Tröster. Multi-Material Systems for Tailored Automotive Structural Components. *18th International Conference on Composite Materials ICCM-18, Jeju, Korea,* August 21-26 2011.

[4] R. Heuss, N. Müller, W. van Sintern, A. Starke, A. Tschiesner. *Lightweight, heavy impact: How carbon fiber and other lightweight materials will develop across industries and specifically in automotive,* McKinsey&Company, 2012.

[5] O. Täger, A. Plath. Bedeutung des Leichtbaus für die Automobilindustrie. *thermoPre Fachtagung 2013: Großserientaugliche thermoplastische Strukturen, Chemnitz, Germany,* August 28-29 2013.

[6] E. Karbe. Leichtbau im Automobilbau. *Leichtbau als Schlüsseltechnologie für Bremen, Bremen, Germany,* December 3 2013.

[7] O. Plath. Potentiale für automobile Fahrzeugstrukturen in hybriden Bauweisen. *Wissenschaftstag 2014: Potentiale für Hybridbauweisen, Braunschweig, Germany,* October 2 2014.

[8] H. Eickenbusch, O. Krauss. *Werkstoffinnovationen für nachhaltige Mobilität und Energieversorgung*. VDI-Gesellschaft Materials Engineering, 2014.

[9] O. Täger. How to make fiber reinforced polymers mainstream? - New hybrid material concepts for cost-efficient automotive lightweight solutions. *LIGHTer International Conference 15, Gothenburg, Sweden,* November 17-18 2015.

[10] Automobil Produktion. IHS: *Neuer 7er BMW kann Mercedes S-Klasse bei Absatz nicht gefährden.* 6/11/2015, Available from: http://www.automobil-produktion.de/hersteller/wirtschaft/ihs-neuer-7er-bmw-kann-mercedes-s-klasse-bei-absatz-nicht-gefaehrden-389.html.

[11] BMW Group. *Investor Presentation: Strategy Number One > Next*. 2016, available online at https://www.bmwgroup.com/content/dam/bmw-group-websites/bmwgroup_com/ir/downloads/en/2015/Investor_Presentation_March_2016.pdf, checked on 4/1/2016.

[12] S. Mazdumar. *Opportunity and Challenges in Automotive Composites Industry*; Lucintel, 2013.

[13] G. Kempf. High-Volume Carbon Fiber Composites in Automotive Applications. *Symposium on the occasion of the 5th anniversary of the Institute for Carbon Composites, Munich, Germany,* September 11-12 2014.

[14] M. Ehleben. Neue Verfahren zur Herstellung thermoplastischer Faserverbundbauteile für die automobile Serienfertigung. *thermoPre 2. Fachtagung: Neue Technologien für faserverstärkte thermoplastische Halbzeuge und Bauteile. Chemnitz, Germany*, September 17-18 2014.

[15] M. Wacker. Hochleistungsfaserverbunde in der Großserie. *Vortragsforum Leichtbau Perspektiven. Gurten, Austria,* October 17 2012.

[16] H. Ferkel, H. Kurz, J-W. Becke. Faserverbundwerkstoffe als wirtschaftliche Option für die Großserie. *CCeV Automotive Forum 2010, Neckarsulm, Germany,* June 24 2010.

[17] A. Erber. High Volume Composite Production: Challenges and Technological Solutions. *LIGHTer International Conference 15, Gothenburg, Sweden,* November 17-18 2015.

[18] D. Grewell, A. Benatar. Welding of Plastics: Fundamentals and New Developments. *International Polymer Processing,* 22(1):43–60, 2007.

[19] C. Ageorges, L. Ye, M. Hou. Advances in fusion bonding techniques for joining thermoplastic matrix composites: a review. *Composites Part A: Applied Science and Manufacturing,* 32(6):839–857, 2001.

[20] A. Yousefpour, M. Hojjati, J. Immarigeon. Fusion Bonding/Welding of Thermoplastic Composites. *Journal of Thermoplastic Composite Materials,* 17(4):303–341, 2004.

[21] V.K. Stokes. Joining methods for plastics and plastic composites: An overview. *Polymer Engineering and Science,* 29(19):1310–1324, 1989.

[22] A.P. da Costa, E.C. Botelho, M.L. Costa, N.E. Narita, J.R. Tarpani. A Review of Welding Technologies for Thermoplastic Composites in Aerospace Applications. *Journal of Aerospace Technology and Management,* 4(3):255–265, 2012.

[23] I. de Baere, W. van Paepegem, J. Degrieck. Fusion bonding of carbon fabric reinforced polyphenylene sulphide. *EPJ Web of Conferences,* 6:08005, 2010

[24] S. Berger, M. Schmidt. Laser Transmission Welding of CFRTP Using Filler Material. *Physics Procedia,* 56:1182–1190, 2014.

[25] V. Wippo, P. Jaeschke, M. Brueggmann, O. Suttmann, L. Overmeyer. Advanced Laser Transmission Welding Strategies for Fibre Reinforced Thermoplastics. *Physics Procedia,* 56:1191–1197, 2014.

[26] W. Knapp, S. Clement, C. Franz, M. Oumarou, J. Renard. Laser-bonding of long fiber thermoplastic composites for structural assemblies. *Physics Procedia,* 5:163–171, 2010.

[27] W. Grouve. *Weld strength of laser-assisted tape-placed thermoplastic composites.* University of Twente, Enschede, The Netherlands, 2012.
[28] G. Jandali, P.K. Mallick. Vibration welding of a unidirectional continuous glass fiber reinforced polypropylene GMT. *Composites Part A: Applied Science and Manufacturing,* 36(12):1687–1693, 2005.
[29] T. Czigány, Z. Kiss. Friction Stir Welding of Fiber Reinforced Polymer Composites. *18th International Conference on Composite Materials ICCM-18, Jeju, Korea,* August 21-26 2011.
[30] I.F. Villegas. Strength development versus process data in ultrasonic welding of thermoplastic composites with flat energy directors and its application to the definition of optimum processing parameters. *Composites Part A: Applied Science and Manufacturing,* 65:27–37, 2014.
[31] M. Dubé, P. Hubert, A. Yousefpour, J. Denault. Resistance welding of thermoplastic composites skin/stringer joints. *Composites Part A: Applied Science and Manufacturing,* 38(12):2541–2552, 2007.
[32] D. Stavrov, H. Bersee. Resistance welding of thermoplastic composites-an overview. *Composites Part A: Applied Science and Manufacturing,* 36(1):39–54, 2005.
[33] H. Shi, I.F. Villegas, H. Bersee. Strength and failure modes in resistance welded thermoplastic composite joints: Effect of fibre–matrix adhesion and fibre orientation. *Composites Part A: Applied Science and Manufacturing,* 55:1–10, 2013.
[34] T. Bayerl, M. Duhovic, P. Mitschang, D. Bhattacharyya. The heating of polymer composites by electromagnetic induction – A review. *Composites Part A: Applied Science and Manufacturing,* 57:27–40, 2014.
[35] R. Rudolf, P. Mitschang, M. Neitzel. Induction heating of continuous carbon-fibre-reinforced thermoplastics. *Composites Part A: Applied Science and Manufacturing,* 31(11):1191–1202, 2000.
[36] P. Mitschang, M. Hümbert, L. Moser. Susceptorless Continuous Induction Welding of Carbon Fiber Reinforced Thermoplastics. *19th International Conference on Composite Materials ICCM-19, Montreal, Canada,* July 28 – August 2 2013.
[37] T. J. Ahmed, D. Stavrov, H. Bersee, A. Beukers. Induction welding of thermoplastic composites – an overview. *Composites Part A: Applied Science and Manufacturing,* 37(10):1638–1651, 2006.
[38] S. Yarlagadda, H.J. Kim, J.W. Gillespie, N.B. Shevchenko, B.K. Fink. A Study on the Induction Heating of Conductive Fiber Reinforced Composites. *Journal of Composite Materials,* 36(4):401–421, 2002.
[39] K. Drechsler, S. Zaremba, P. Fröhlich, W. Raffelt, A. Schwingenschlögl. *Manufacturing Technologies for Composite Parts: 15 Finishing II – Joining Technologies*. Institute for Carbon Composites, TUM, 2014.
[40] Delo Industrie Klebstoffe GmbH & Co. KGaA. ONSERT: The Best of Both Worlds: Joining of Composite Materials [Part2]. *DELO news 09/2015*. 2015.
[41] F. Dirschmid. Die CFK-Karosserie des BMW i8 und deren Auslegung. *Karosseriebautage Hamburg, Hamburg, Germany,* May 14-15 2014.
[42] S. Deng, L. Djukic, R. Paton, L. Ye. Thermoplastic-Epoxy Interactions and their potential Applications in Joining Composite Structures – *A Review. Composites Part A,* 68: 121-132, 2015
[43] C.B. Bucknall, I. K. Partridge. Phase separation in epoxy resins containing polyethersulphone. *Polymer,* 24: 639-644, 1983
[44] J.H. Hodgkin, G. P. Simon, R. J. Varley. Thermoplastic Toughening of Epoxy Resins: A Critical Review. *Polymers for Advanced Technologies,* 9: 3-10, 1998
[45] G. Di Pasquale, O. Motta, A. Recca. New High-Performance Thermoplastic Toughened Epoxy Thermosets. *Polymer,* 38: 4345-4348, 1997
[46] C. Bucknall, A. H. Gilbert. Toughening Tetrafunctional Epoxy Resins using Polyetherimide. *Polymer,* 30: 213-217, 1989
[47] R.J.J. Williams, B. A. Rozenberg, J.-P. Pascault. Reaction-induced Phase Separation in Modified Thermosetting Polymers. *Advances in Polymer Science,* 128: 95-156, 1997
[48] P. Bruckbauer., F. Weiland, U. Beier, K. Drechsler. Characterization of thermoplastic/thermoset combinations – potential application for joining. *Proceedings of the European Conference of the*

Excerpt from ISBN 978-3-00-053387-7

Society for the Advancement of Material and Process Engineering (SAMPE), Amiens, France, September 15-17, 2015

[49] R.C. Don, J. W. Jr. Gillespie, S. H. McKnight. Bonding Techniques for High Performance Thermoplastic Compositions. *US Patent* No. 5643390, 1997.

[50] M. Hou. Thermoplastic Adhesive for Thermosetting Composites. *Trans Tech Publications, Materials Science Forum*, Vols. 706-709:2968-2973, 2012

[51] A.J. Comer, D. Ray, W.O. Obande, D. Jones, J. Lyons, I. Rosca, R.M. O'Higgins, M.A. McCarthy. Mechanical characterisation of carbon fibre–PEEK manufactured by laser-assisted automated-tape-placement and autoclave. *Composites Part A: Applied Science and Manufacturing*, 69: 10–20, 2015.

[52] V. Radlmaier, G. Obermeier, S. Ehard, A. Kollmannsberger, H. Koerber, E. Ladstaetter. Interlaminar fracture toughness of carbon fiber reinforced thermoplastic in-situ joints. *Proceedings of the Polymer Processing Society Conference (PPS), Graz, Austria*, September 21-25 2015.

[53] F. Henne, S. Ehard, A. Kollmannsberger, B. Höck, M. Sause, K. Drechsler. Thermoplastic in situ fiber placement for future solid rocket motor casing manufacturing. *Proceedings of the SAMPE Europe SETEC 14 - Efficient composite solutions to foster economic growth Conference, Tampere, Finland*, September 9-11, 2014.

[54] V. Radlmaier, S. Ehard, E. Ladstätter, K. Drechsler. Thermoplastic automated fibre placement: current fields of application and future prospects. *JEC Composites Magazine*, 97:39-42, 2015.

[55] S. Ehard, A. Mader, E. Ladstätter, K. Drechsler. Thermoplastic automated fiber placement for manufacturing of metal-composite hybrid parts. *Proceedings of the 2nd International Conference Euro Hybrid Materials and Structures*, *Kaiserslautern, Germany,* April 20-21, 2016.

[56] S. Ehard, E. Ladstätter, M. Jürgens, L. Bortolotto, N. Remer. Development of a Hybrid Tail Rotor Drive Shaft by the Use of Thermoplastic Automated Fiber Placement. *Proceedings of the 17th European Conference on Composite Materials ECCM17, Munich, Germany,* June 26-30, 2016.

Excerpt from ISBN 978-3-00-053387-7