

Influence of cathodic dip painting on the mechanical strength of material-adapted composite/metal joints

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DOI: [dx.doi.org/10.14314/polimery.2018.11.2](https://doi.org/10.14314/polimery.2018.11.2)

Abstract: The flow drill joining concept (FDJ) allows the load adjusted joining of continuous fiber reinforced thermoplastics (FRTP) and metallic sheets without auxiliary joining elements. As there is no scathe done to the fiber reinforcement, a radial realignment of the fibers leads to high-strength joints with high lightweight potential. In terms of their use in automotive lightweight construction, an important requirement for joining technologies is the resistance to temperature loads and chemicals, applied in the production processes, *e.g.*, in vehicle lacquering. Therefore, force flux aligned FDJ-joints were investigated in cross tension and shear testings, after passing through a serial cathodic dip painting (CDP) process. The results show that the CDP-treatment does not adversely affect the quasi-static properties of the tested FDJ-joints, as they resist shear loads up to 2900 N and cross tension loads of about 1100 N, both, before and after the lacquering process.

Keywords: continuous fiber reinforced thermoplastics (FRTP), cathodic dip painting, joining, flow drill joining concept (FDJ).

Wpływ lakierowania katodowego na wytrzymałość mechaniczną połączeń metalu z termoplastycznymi kompozytami wzmocnionymi włóknami ciągłymi

Streszczenie: Metoda wykorzystująca wiertło tarciove Flowdrill (*flow drill joining*, FDJ) umożliwia łączenie metalu z kompozytami termoplastycznymi wzmocnionymi włóknami ciągłymi (FRTP) bez udziału pomocniczych elementów łączących. W metodzie tej włókna w kompozycie nie są przecinane jak w klasycznym sposobie łączenia, ale rozszerzane, co sprawia, że połączenie cechuje się dużą wytrzymałością. Technika FDJ potencjalnie może być stosowana do konstrukcji lekkich. Ważną cechą wymaganą od wykorzystywanych w przemyśle samochodowym elementów wykonanych wg tej technologii łączenia jest odporność na obciążenia temperaturowe i chemiczne towarzyszące procesom produkcyjnym, takim jak lakierowanie katodowe (CDP). Stwierdzono, że obróbka CDP nie wpływa niekorzystnie na właściwości quasi-statyczne badanych połączeń FDJ, wytrzymują one obciążenia sił ścinających do 2900 N i krzyżowych do ok. 1100 N zarówno przed, jak i po procesie lakierowania.

Słowa kluczowe: kompozyty termoplastyczne wzmocniane włóknami ciągłymi (FRTP), lakierowanie katodowe, łączenie, metoda łączenia przy użyciu wiertła tarciove *flow drill joining* (FDJ).

Due to the achievable synergy effects, continuous fiber reinforced thermoplastics are increasingly applied in automotive lightweight design [1]. Novel vehicles, like BMW i8 or Audi A6 are already in use of mounting parts, such as the diffuser frame or infotainment carriers [2, 3]. In order to receive a higher level of mass reduction, the use of continuous fiber reinforced ther-

moplastics (FRTP) will be extended to structural components in the near future. To fully exploit the high lightweight potential of these lightweight materials in these high-stressed areas, new material-adapted joining techniques have to be developed, since conventional joining methods – such as screwing or riveting – do not meet the needs of continuous fiber reinforced polymers in a satisfactory manner. Rather, they cause damage to the filigree fiber structure since they are based on drilled holes or joining elements with cutting edges (*e.g.*, semi-hollow rivets). Therefore, the structural architecture of the anisotropic FRTP necessitates new and optimized solutions for a material-adapted joining with high load capacities that also consider the challenges of multi-ma-

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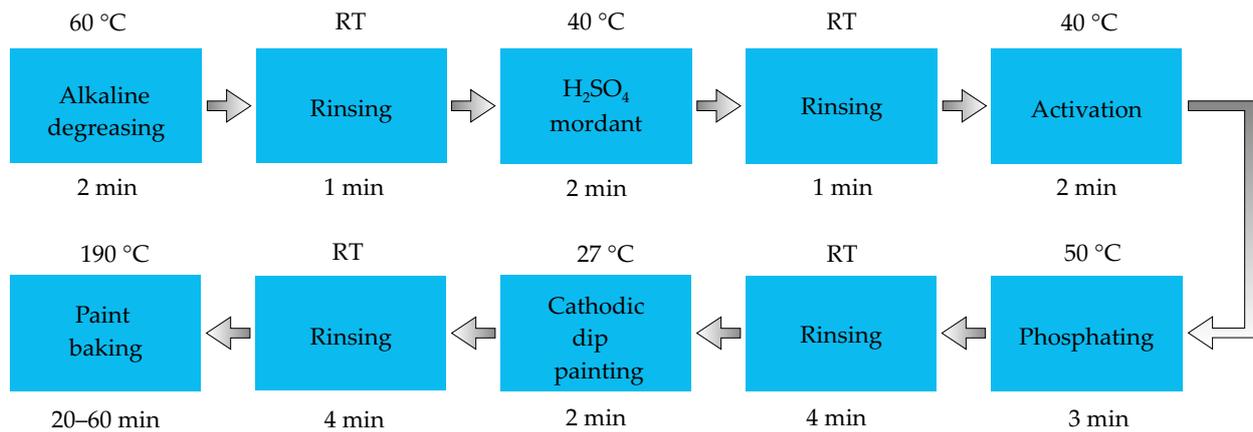


Fig. 1. Cathodic dip painting process

terial design between FRTP and the mostly metallic surroundings of car bodies.

In this regard, one new approach is the innovative flow drill joining concept (FDJ), developed at the Institute of Lightweight Structures (IST) of the Chemnitz University of Technology. It combines metal- and FRTP-thermoforming processes and enables a fault tolerant and reproducible joining of these various material systems. Due to an *in situ* fiber realignment in the FRTP load introduction zone, a high stressable force flux optimized design of the joint is achieved, whereby no additional joining element is required which suffers significant advantages in weight and costs of multi-material designs.

After numerous investigations on parameter studies, design rules and material combinations [4–6], the novel joining technique has to be qualified for the use in conventional automotive manufacturing processes. Since all car body structures are passing through a conventional automotive process chain, the joining techniques need to be resistant to all temperature loads and chemicals, applied during the production processes, *e.g.*, in vehicle lacquering. Therefore, force flux aligned FDJ-joints were investigated in cross tension (DIN EN ISO 14272) and shear testings (DIN EN ISO 14273), before and after passing through one serial cathodic dip painting process, as shown in Fig. 1.

EXPERIMENTAL PART

Materials

In the current study, FDJ-joints made of continuous carbon fiber (HT) reinforced polyamide 6 (sheet thickness $t = 2.4$ mm) and a representative hot-dip-coated and galvanized micro-alloyed steel (HX420LAD+Z100, $t = 1.5$ mm) were examined. The FRTP was made of unidirectional prepreg tapes (PA6-CF60), stacked and formed to a symmetric, orthotropic $[(0/90)_4]_s$ -composite with a fiber volume content of 48 wt %. The mechanical properties of both, the composite layers and the HX420LAD+Z100 sheets are shown in Table 1.

Flow drill joining concept

With the use of the automated FDJ process, the high lightweight potential of multi-material designs with FRTP and modern metal alloys can be utilized in a more efficient way. Compared to well known joining technologies, like riveting or bolting, there is no negative affection of the basic materials by damaging the fiber structure due to machined boreholes or cutting edges of, *e.g.*, self-piercing rivets [4]. Furthermore, next to a renunciation of auxiliary joining elements, there are no cost-intensive operations, such as grinding, etching or degreasing, necessary.

The multi-stage joining process is shown schematically in Fig. 2 and can be described by the three main steps: 1 – plasticizing of the thermoplastic matrix, 2 – forming of a metallic bushing with a flowdrill, 3 – forming of a closing head to realize a form lock between FRTP and metal sheet.

The rotating mandrel is applied to the upper side of the metallic sheet first, and forms the required bushing throughout the plasticized FRTP in two phases afterwards. The first phase (feed rate v_1) serves the heat influx to increase the plasticity of the metal sheet. By forming the bushing through the previously plasticized FRTP with higher speed (feed rate v_2), the containing reinforcing fibers are redirected tangentially, and therefore non-destructive, around the punctiform joint. The sectioned processing with two feed rates allows a defined energy input into the metallic part, to guarantee a high quality

Table 1. Mechanical properties of basic materials

Parameter	PA6-CF60	HX420LAD+Z100
Young's modulus (E_{II}), GPa	98	210
Tensile strength (σ_m), MPa	1938	470–590
Fiber volume (ϕ), %	48	–
Layer structure	$[(0/90)_4]_s$	–
Layer thickness (t_l), mm	0.15	–
Sheet thickness (t), mm	2.4	1.5

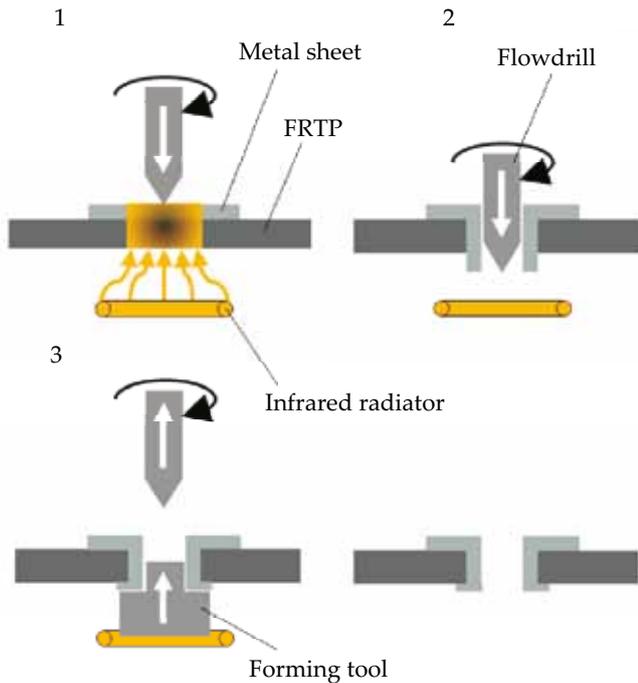


Fig. 2. Principle of manufacturing a load adjusted FDJ-joint

of the bushing for every material, and a reduction of processing time (Fig. 3). In a final step, an overleaf forming tool folds the bushing with a defined force F_U to obtain a traction and form lock between the two basic materials.

As a result of the process-induced fiber realignment and the displacement of the thermoplastic matrix, a local accumulation of material occurs in the fringe of the joining area. According to that and in contrast to established technologies, FDJ-joints contain a process-related reinforcement in the critical areas next to the joint [4].

The process parameters of the FDJ-joints used in this study are summarized in Table 2.

Cathodic dip painting

The cathodic dip painting (CDP) is an electrochemical coating process, which has proven itself a very uniform coating of metal surfaces and cavities with consistent layer thicknesses and good surface qualities in vehicle construction. The CDP primer is used to protect struc-

Table 2. Process parameters of FDJ-joints

Parameter	Value
Sheet thickness t , mm	2.4/1.5
Diameter of the joint d_p , mm	5.3
Diameter of the melting area d_s , mm	20
Rotational speed of flowdrill n , rpm	3000
Feed rate v_1 , mm/min	300
Feed rate v_2 , mm/min	1300
Change-over point l , mm	1.0
Forming force F_U , kN	18

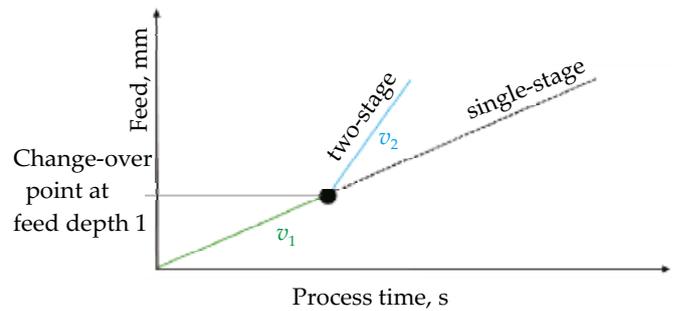


Fig. 3. Feed rates v and change over point l

tures against corrosion and serves as an adhesion base for subsequent coatings [7].

Due to the inconsistent temperature profile, with top temperatures in the range of 130 °C to 190 °C, and the highly divergent coefficients of thermal expansion in FRTP and metals, the baking of lacquers represents a particularly critical load for joints in multi-material design. Thus, thermally induced residual stresses can lead to damages if the joining technology is not suitable for CDP treatments.

The traversed temperature profile of the tested CDP process shows an approximately 35 minutes lasting, steady heating of the specimen. As to be seen in Fig. 4 the duration of the baking process with a maximum temperature of 190 °C (± 2.8 °C) takes about 20 minutes, followed by a rapid cooling to 29 °C (± 3.9 °C) within about 5 minutes.

Methods of testing

The conducted experiments and specimen geometries are based on the standard testings for resistance spot-welded joints: DIN EN ISO 14272 and DIN EN ISO 14273 (Table 3). Due to its importance for the automotive industry, resistance spot-welding has a broad normative background and is accordingly well documented in terms of testing procedures. Specimen shapes and test parameters can be transferred to the examination of other punctiform joints, which is why they are often used for comparative studies. Unlike material testing the investigation of punctiform joints is mostly limited to the determination of maximum forces.

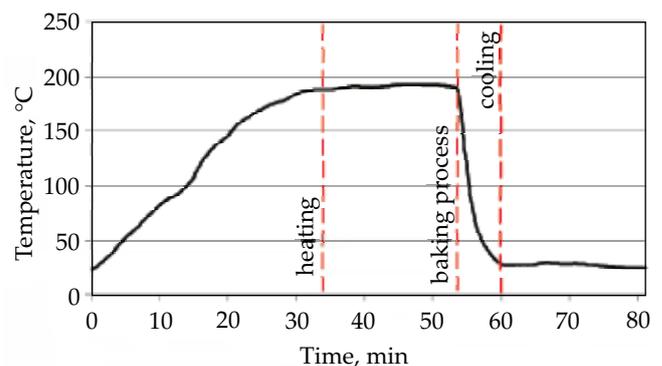
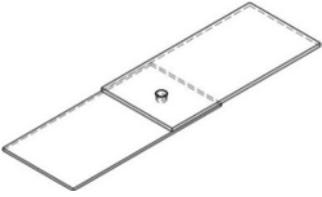
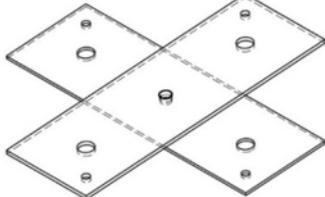


Fig. 4. Temperature profile of tested CDP treatment-paint baking process

Table 3. Specimens according to DIN EN ISO 14272 and DIN EN ISO 14273

		
Test	Shear load	Cross tension
Standard	DIN EN ISO 14273	DIN EN ISO 14272
Width	50.0 mm	
Thickness	FRTP = 2.4 mm/metal = 1.5 mm	
Edge distance	17.5 mm	25.0 mm
Overlap	35.0 mm	50.0 mm

The investigations of this study are quasi-static (testing speed 2 mm/min) and were carried out on a tensile testing machine according to DIN 51220 with measuring equipment according to DIN EN ISO 7500-1. The loads were increased slow, shock-free and steady until failure of the specimens. The room temperature was 23 °C with a humidity of 50 %, as mentioned in DIN EN ISO 291.

RESULTS AND DISCUSSION

The results of the cross tension and shear testings in accordance to DIN EN ISO 14272 and 14273 confirm the high strength and strong resistance of PA6-CF-based FDJ-joints against thermal and medial loads within the cathodic dip painting process. A comparison to specimens in untreated conditions shows no significant impact of the CDP process on the tolerable quasi-static shear and cross tension forces (Fig. 5). The findings are underlined by [3], where it is said that the fiber-dominated properties of PA6-based FRTP are not affected by CDP treatment. A presumed effect on the maximal tolerable forces – in consequence of adhesive CDP-depositions between FRTP and metal – could also not be confirmed because the strength of the FDJ-joints superimposes the properties of the cathaphoresis coating.

CONCLUSIONS

In terms of their use in automotive lightweight construction, an important requirement for joining technologies is the resistance to temperature loads and chemicals, applied in the production processes, e.g., in vehicle lacquering. Therefore, force flux aligned FDJ-joints were investigated in cross tension and shear testings, after passing through a serial cathodic dip painting process. The results show that the cathodic dip painting process does not adversely affect the static properties of the tested FDJ-joint and confirm the high strength and strong resistance of PA6-CF-based FDJ-joints against thermal and medial loads. In further investigations, the effects on fatigue strength will be examined.

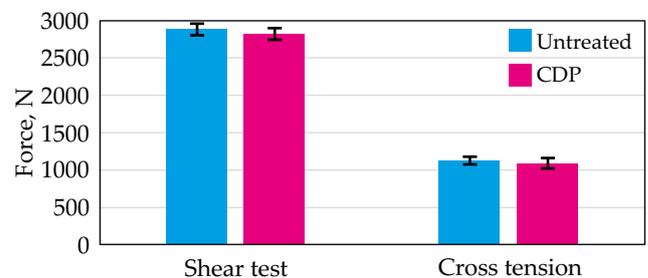


Fig. 5. Results of shear and cross tension tests (5 specimens per each test condition)

ACKNOWLEDGMENTS

The presented studies were performed as part of a pre-investigation within the Federal Cluster of Excellence EXC 1075 “MERGE Technologies for Multifunctional Lightweight Structures” and supported by the German Research Foundation (DFG) to explore integrative processes with plastic/metal composites. Financial support is gratefully acknowledged.

REFERENCES

- [1] Goede M., Stehlin M., Rafflenbeul L. *et al.*: *European Transport Research Review* **2009**, 1, 5. <http://dx.doi.org/10.1007/s12544-008-0001-2>
- [2] Osiecki T., Gerstenberger C., Hackert A. *et al.*: *Key Engineering Materials* **2017**, 744, 311. ISBN-13 978-3-0357-1116-5. <http://dx.doi.org/10.4028/www.scientific.net/KEM.744>
- [3] Grätzl T., Schramm N., Kroll L.: “Influence of the Cathodic Dip Painting Process on Fibre-Reinforced Thermoplastic Composites”, Proceedings of the 3rd International Conference & Exhibition on Thermoplastic Composites ITHEC, Bremen (Germany), 1112. 10. 2016. ISBN: 978-3-933339-29-4.
- [4] Seidlitz H.: “Entwicklung von kraftflussgerechten Verbindungstechniken für Mischbauweisen mit thermoplastischen Faserverbunden und Metallen”,

- Dissertation, TU Chemnitz, 2013. Verlag Dr. Hut.
ISBN: 978-3-8439-0961-7.
- [5] Seidlitz H., Ulke-Winter L., Kroll L.: *Journal of Engineering* **2014**, 2014, ID 958501.
<http://dx.doi.org/10.1155/2014/958501>
- [6] Seidlitz H., Ulke-Winter L., Gerstenberger C., Kroll L.: *Open Journal of Composite Materials* **2014**, 4 (3), 157. ISSN 2164-5612.
<http://dx.doi.org/10.4236/ojcm.2014.43018>
- [7] Gerstenberger C., Osiecki T., Kroll L. et al.: *Archives of Civil and Mechanical Engineering* **2016**, 16, 467.
<http://dx.doi.org/10.1016/j.acme.2016.03.001>
- Received 23 XII 2017.