

THERMAL DIRECT JOINING OF METAL TO FIBER REINFORCED THERMOPLASTIC COMPONENTS

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Abstract

In the field of lightweight construction load-capable mixing compounds with the material specific advantages of metal and thermoplastic become increasingly significant. For this efficient process chains including adapted pre-treatment and joining processes in combination with process simulation tools are required. Post- or in-mold assembly processes, mechanical joining by screws or rivets and adhesive bonding are state-of-the-art techniques for joining dissimilar materials such as metal and thermoplastics [1, 2]. Specific restrictions can be found at the limited geometry flexibility, the use of additional material and comparable long joining times. Hence new joining solutions are needed.

Within this presentation the use of thermal induced joining for metal - thermoplastic parts will be shown. These processes are characterized by short joining times and the substitution of glue, screws or rivets. The key technology to enable high joint strengths is the material adapted surface modification. As a research result the influence of physical and chemical pre-treatment will be presented. It could be shown that metal ablation by high power lasers can efficiently generate a macroscopic surface structure, which enables mechanical fastening of the polymer at the metal surface. Depending on the materials to be joint different kind of heat input can be used. Within this presentation the joining by hotplates and by laser will be introduced. It will be shown, that an optimized surface pre-treatment enables joints with lap shear strengths of 20 N/mm² and more, depending on the material configuration.

Introduction

The sensible use of resources requires new technology developments in the field of lightweight constructions. Contemplated from material side multi material concepts are the focus of new developments. The intensified use of high-performance fiber composites and polymers and the strategy of complex constructions with “material choosing on local demand” are common trends [1, 2]. To integrate these high-optimized parts into the structure efficient joining techniques are required.

While the production of polymer and composite parts are favorable be done by molding or/and forming processes with comparable high tool costs, differential constructions with integrated functions can cost-efficiently be done by well-suited joining techniques. The global development aims are:

- Automated processes with short cycle times
- Possibility of integrated online quality control
- Preservation of environment and energy resources
- Industry accepted costs - performance relation

Joining processes based on a mostly adhesion bond are state of the art for composite-metal joints. Here the properties of the adhesive define the joint characteristic: structural bond, sealing bond, bridging bond, etc. [3].

The development of multi material joining processes based on optimized adhesion with or without glue is characterized by the following steps, shown in figure 1.

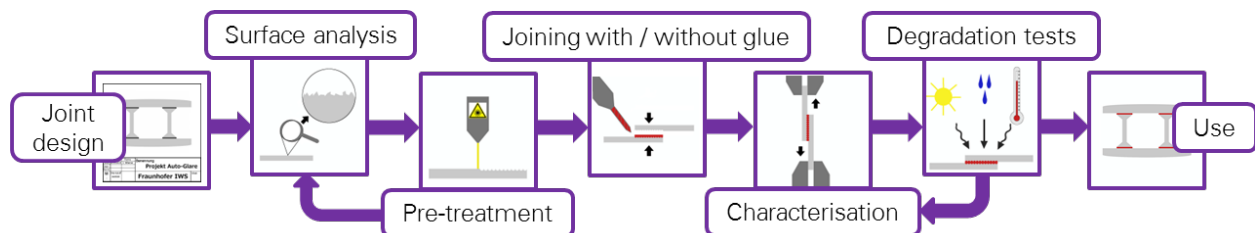


Figure 1: Process chain of adhesive joining process

Depending on the connection requirements and determined load the geometry and layout of the joining partner has to be defined. Afterwards the surfaces have to be cleaned and pre-treated to guarantee good adhesion behavior. Depending on the kind of material to be joined different treatment processes are favorable to use (see chapter *surface pre-treatment*). The joining process itself (with or without glue) is mostly done or started by heat assistance. Depending on the kind of adhesive the joining process is finished after some seconds (cyanoacrylate or hotmelts) or up to 24 hours and more (two-component adhesive).

Based on the adhesion mechanism at the interface between both partners the local strength is lower than it can be reached with other joining technologies like mechanical joining or welding. But by increasing the surface area acceptable joint strengths up to values of the base material are possible.

To characterize the joint behavior degradation tests and afterwards destructive testing have to be executed, before transferring to industrial use.

Thermal direct joining

The joining of metal and thermoplastic by heat is allocated to the category of „press welding with heat“ (DIN-8593) [4]. At the market there are different technical solutions for the melting of the thermoplastic joining partner available [5, 6, 7, 8, 9, 10]:

- Heating by friction (e.g. friction stir welding, grind riveting) [11]
- Thermo-clinching
- Heating by ultrasonic or microwave
- Heating by heat conduction with hotplates
- Induction or conduction heating of metal or carbon fibers within the polymer [12]
- Heating by reactive multilayer foils (RMS) as an exothermic storage (figure 2c) [13]
- Laser transmission welding (figure 2a) [14, 15]
- Laser induced metal heating (figure 2b) [16, 17, 18, 19, 20, 21, 22, 22, 23]

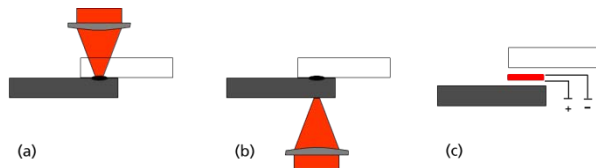


Figure 2: Process principles of metal-polymer joints: (a) laser transmission welding, (b) laser induced metal heating, (c) joining with reactive multilayer systems (RMS)

Within this presentation two kinds of heat input will be introduced and compared. First technology is the joining by hotplates, well established at the industry. The other technology discussed within this paper and

shown in figure 2b uses laser radiation for intense and local metal heating. The thermoplastic joining partner will be pressed to the metal during the laser heating process. Based on heat conduction from the metal part the polymer will locally be melted. The liquidized polymer will wet the metal surface, solidifies and generates the adhesion bond. If service conditions are demanding, for example, if the joints will be exposed to water or to high stresses, then physical and chemical pre-treatments are recommended.

Surface pre-treatment

Sufficient adhesion of the parts to be joined is a precondition for surface sensitive joints. To guarantee good adhesion on real components, the surfaces have to be pre-treated [3].

Laser treatment is frequently used as a technology that provides stability in the long term and makes it possible to remove organic and inorganic contamination, coatings (e.g. paints) or residues from manufacturing (oils, lubricants) by means of Nd:YAG and fiber lasers in a selective and reproducible manner.

The removal by means of the laser not only cleans surfaces, but also significantly extends the areas available for adhesion. Thus, for instance, macrostructural texturing as a pre-treatment for thermal direct joining of metals and thermoplastics provides an optimal form-fit to achieve high joint strength.

In the manufacture of light metals, such as aluminium, adequate laser parameters can result in the removal of the native oxide layer and the formation of a new homogeneous oxide layer, providing a good foundation for bonding [24, 25].

As a function of the materials to be manufactured and productivity requirements, it is possible to apply either pulsed lasers of different wave length (UV, VIS, IR, NIR lasers) or continuous wave high-brilliant lasers [26].

To establish intermolecular forces between metal substrates and polymer the application of a primer solution based on organosilane adhesion promoter may be used to ensure the required durability of the joint [3]. The primer solutions, used for the actual thermal direct joining experiments between metal and fiber reinforced polymers, are mostly co-polyamides. The kind of processing (application, temperature cycles for curing/activating) differs strongly between solutions of different commercial providers. Hence comparative tests were done during laser and hotplate induced thermal direct joining.

Thermal direct joining by hotplate

The fabrication of hybrid laminates, made of metal and fiber reinforced thermoplastics is favorable be done by hot pressing / hot forming processes. Here the joining partner will be pressed and heated to the melting temperatures of the polymer matrix and afterwards will be solidified. For process optimization, the setup, shown in figure 3 was used. With that equipment the test specimens for tensile shear strength testing were fabricated. A multiaxial testing machine was used to produce the test specimen. The joining tool consists of a hotplate and a cooling plate (above) and an adjustable unit for polymer fixing (below).

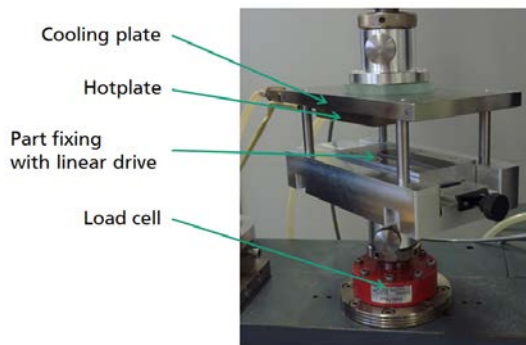


Figure 3: Processing setup for thermal direct joining by hotplate

The metal part will be heated up to the determined temperature, controlled by an integrated thermocouple. Afterwards the parts will be force-controlled pressed together. Subsequently the cooling process starts. In figure 4 a typical force-time diagram is shown. Based on the heating principle the whole metallic parts will be heated up completely by heat conduction. This procedure results to relatively long joining times and high stresses within the parts at ambient temperature.

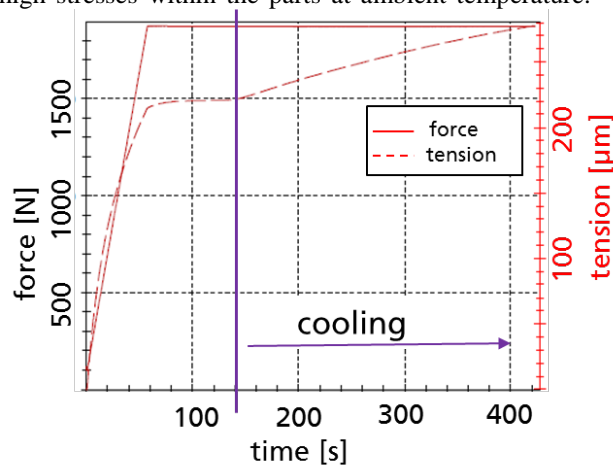


Figure 4: Force-time diagram at a characteristic thermal direct joint with hotplate between mild steel and glass fiber reinforced polyamide PA6

Thermal direct joining by laser radiation

Laser radiation enables local warming with very high heating rates. Using high power cw laser, temperature gradients of more than 500°C / second are used to minimize the joining times. The local heat input to the metallic joining partner will be realized by means of a fiber laser in combination with a galvanometer scanner system. The high speed beam deflection enables a uniform heat input independently of irregular heat conduction. The experimental setup is shown in figure 5.

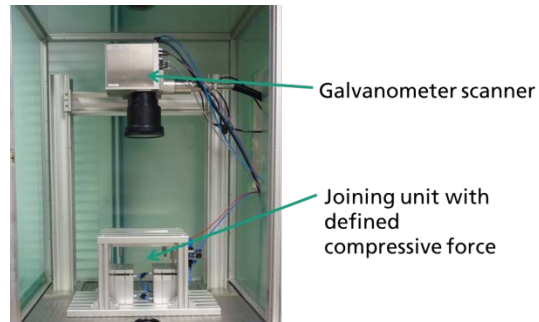


Figure 5: Processing setup for thermal direct joining by laser

Experimental results and discussion

Material and experimental matrix

During the scientific study different material combinations were tested for hotplate and laser assisted joining. Table 1 shows an extract of material combinations.

Table 1: Overview of material and process combinations

Metal	mild steel, stainless steel, aluminium	1.5 mm thick
Polymer	Tepex [®] dynalite (PA6 + glass fiber, 47% FVC)	2 mm thick
Pre-treatment of metal	reference	ethanol
	sand blasting	corund
	laser (table 2)	laser I; laser II; laser III
	primer	VESTAMELT [®] (Evonik), L-F501 (L&L),
Heating process	hotplate	max. temperature: 350°C
	laser (table 3)	Pl: 2 kW, fiber laser, dynamic beam forming,

All trials were done at test specimens with 25 mm width and 12.5 mm overlap. The samples were analyzed by lap shear tests based on the test standard of adhesion bonding (EN 1465/ASTM D3163). The breaking forces were measured and the fracture surfaces were analyzed. It was shown that different fracture pattern are detectable (cohesive, adhesive, mixed fracture), depending on process parameters.

Surface Pre-treatment

Based on basic knowledge of adhesive bonding processes the parts were pre-treated by laser. To get high productivity a 1 kW cw – fiber laser in combination with a galvanometer scanner system was used (table 2). Depending on the joint geometry and material properties the orientation of the ablation lines and their distance will be adapted. The number of cycles and the laser power determine the ablation depth per line.

Table 2: Process parameter for laser macro structuring

Laser	YLR1000-SM		
Galvanometerscanner	Intelliscan10 (Scanlab AG)		
Focusing length	160 mm		
Spot diameter	30 μm		
Parameter setup	laser 1	laser 2	laser 3
Laser power [W]	1000	900	900
Scanning speed [m/s]	10	10	5
Line distance [μm]	150	150	150
Number of cycles	2	2	3

At the actual trials treatment rates of up to 100 mm²/s were reached to enlarge the surface for sufficient adhesion. Figure 6 shows treatment samples of mild steel with their surface topology.

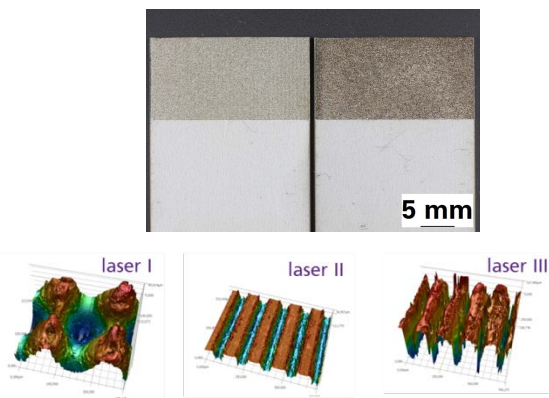


Figure 6: laser macro structuring of mild steel (top left: laser structuring I; right: laser structuring III bottom left: laser structuring I (R_z : 109 μm); middle: laser structuring II (R_z : 115 μm), right: laser structuring III (R_z : 350 μm))

Besides pure physical methods also combinations of physical and chemical methods were tested. Three different primer solutions mostly based on copolyamides were tested. While some primer are available as multilayer foils (company L&L Products), others need additional drying processes after the application as a liquid (Vestermelt®). These process steps are time and cost consuming. Because of that it has to be investigated whether laser structuring as a physical and stable method for long time could generate acceptable joint strengths too.

Thermal direct joining by hotplate

During thermal joining by hotplate the temperature range was between 180°C – 300°C with the variation of joining pressure of 0.25 – 6 N/mm².

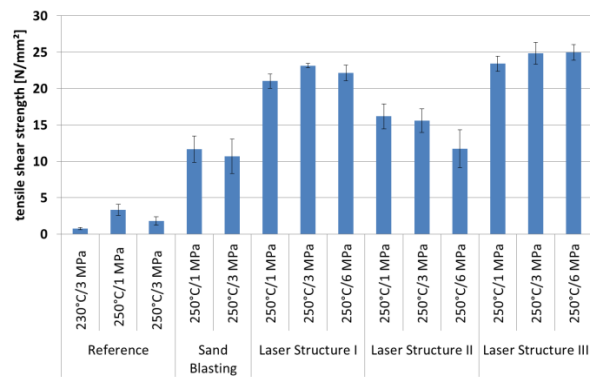


Figure 7: Thermal direct joining with the hotplate process; variation of physical pre-treatment, hotplate temperature and joining pressure; material: mild steel

As shown in figure 7 and 8 physical treatment by laser can drastically increase the joint strength. Depending on the joining parameter tensile strengths of 15 – 25 N/mm² were reached.

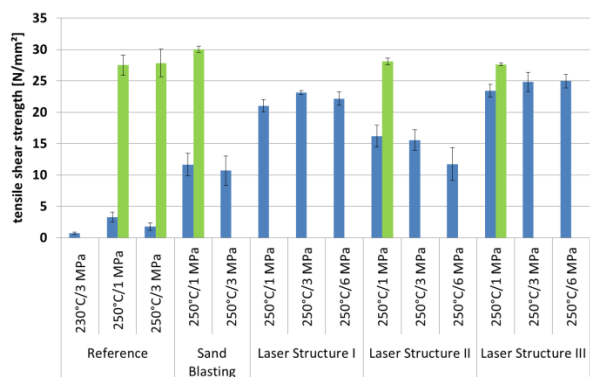


Figure 8: Thermal direct joining with the hotplate process; variation of physical (blue) and chemical pre-treatment with primer (Vestamelt®) (lightgreen), hotplate temperature and joining pressure; material: mild steel

Using chemical pre-treatment with primer solutions (e.g. Vestamelt®) joint strengths up to 30 N/mm² can be obtained.

Thermal direct joining by laser

As shown in Figure 5 a galvanometer scanner was used for the local laser heating. To minimize the warming time of the metal sheets laser power up to 2 kW IR-radiation was used in combination with high speed beam deflection (table 3).

Table 3: Process parameter for laser direct joining

Laser	YLS2000-SM
Galvanometerscanner	Intelliscan20 (Scanlab AG)
Focusing length	340 mm
Spot diameter	5 mm, defocused
Laser power	1000 W – 2000 W
Scanning modus	2-dimensional (lissajous curves)
Number of cycles	3 - 10

Depending on the joining area the defocused laser beam will be oscillated two-dimensionally to generate a uniform temperature distribution within the joining area. Figure 9 shows a characteristic temperature-time plot of the joining process, analyzed by a thermal imaging system. Within the measuring experiments the thermal camera measures the temperature profile at the metal part and calculates min., average and max. temperatures within the joining area.

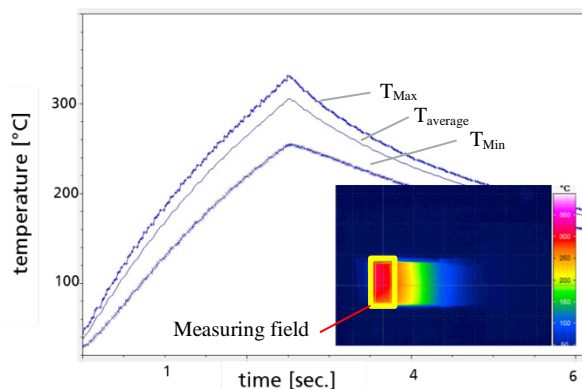


Figure 9: Temperature-time plot (min., average, max.) of laser assisted thermal direct joining; material: aluminium; warming area: 12.5 mm x 25 mm; laser power: 2 kW (fiber laser)

In general comparable tensile strengths could be reached by laser joining compared to joining with hotplates (figure 10). Between 18 to 28 N/mm² were achieved in combination with laser macro structuring. It was observed that the performance of commercial

primer solutions will be decreased based on very short joining and accordingly short primer reaction times.

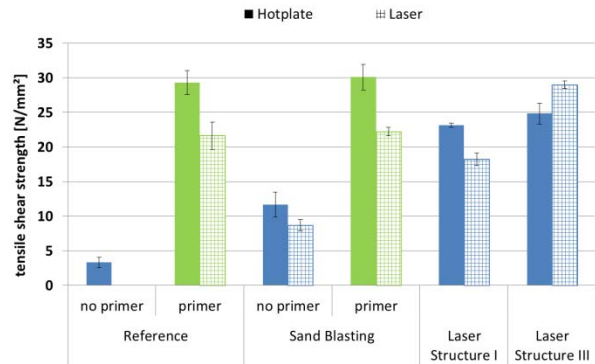


Figure 10: Thermal direct joining with hotplate and laser process: variation of physical and chemical pre-treatment, material: mild steel

Fracture characteristics

After destructive testing the fracture surfaces of the test specimen were analyzed. Depending on the pre-treatment parameters different fracture images were observed. Figure 11 left shows an adhesive fraction. The fiber reinforced polymer (FRP) infills the macroscopic structure of the metal. There is no undercut for mechanical fixing.

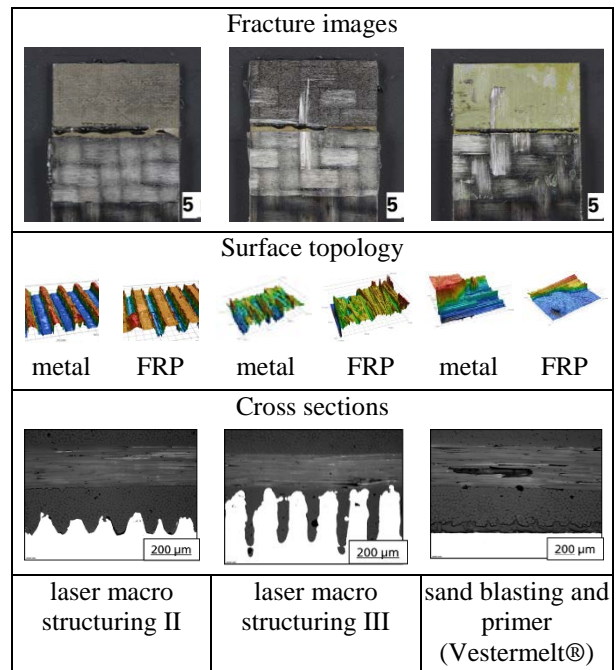


Figure 11: Fracture images with surface topology and cross sections of metal-polymer joints, generated with hotplate technology; variation of pre-treatment: laser macro structuring II (left); laser macro structuring III (middle); sand blasting and primer (right), material: mild steel

Adapting the laser structuring parameter (Figure 11 middle) a mostly cohesive fracture within the polymer could be reached with higher tensile strengths. Thereby the strength of the FRP itself including the fiber-matrix adhesion will be relevant.

Using co-polyamide primer solutions a mostly cohesive fracture image was observed based on intermolecular forces between metal, primer and polymer (Figure 11 right).

Contrary to the pre-treatment by laser no form-fit is realized. Based on the chemical interaction an optimized adhesion and consequential a high tensile strength is reached.

Process productivity and efficiency

The transfer of new joining processes into the industrial production can only be successful, if the joining performance increases while the production costs decreases to an acceptable range. That's why the development presented within this paper was focused to shorten the joining times. Table 4 shows typical joining times for the fabrication of a single tensile test specimen.

The advantage of laser heating is a local controlled intense heat input into the metal. Only the area, directly in contact with the polymer material will be heated up. The energy losses based on heat conduction and heat emission can be minimized. Depending on the material configuration to be joined the heating can be realized within some seconds. After cooling down to solidification temperature of the polymer the joining process is finished.

Table 4 Comparison of joining times for hotplate and laser assisted thermal direct joining

Heating process	metallic joining partner *	Heating time	Cooling time to 200°C
Hotplate	all	5-15 min	2-5 min.
Laser	mild steel	3 sec.	2 sec.
Laser	stainless steel	8 sec.	3 sec.
Laser	aluminium	3 sec.	2 sec.

* materials and thicknesses described in Table 1

Besides the joining process itself also the kind of surface pre-treatment has to be taken into account for the time and cost calculation. Compared to chemical pre-treatment with primer solutions the mechanical cleaning and structuring by cw-laser could be a productive alternative for the industry.

Conclusion

Thermal direct joining of metal and fiber reinforced thermoplastic components has the potential to intensify the trend to multi material construction. Under the condition of optimized surface pre-treatment tensile strengths in the range of 25 – 30 N/mm² were reached. Although the use of primer solution have resulted to highest tensile strength, laser macro structuring showed good strengths with mostly form-fit connections. To investigate the influence of the heating process, hotplate and laser radiation were used for metal warming. Both techniques enable the fabrication of comparable joint performances. Optimizing the process into the direction of minimized joining times, the laser induced joining process could be realized within some seconds compared to a hotplate process, which takes more than 10 minutes.

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