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Laser joining of textured metal and plastic components

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Abstract

Laser joining of plastic-metal-hybrid-compounds is the subject of a number of research-exploits worldwide. In parallel, first applications start to emerge, in particular in the automotive sector in the quest of lowering the weight of cars and trucks. Drive trains, gaskets, car body stiffening elements, and other applications may make use of polymer components in conjunction with classical metal structures. Evidently, laser joining of polymers to metals presents significantly greater challenges compared with standard welding processes.

We present recent progress in laser joining processes, including metal texturing, joining the hybrid material, and stress testing. The gamut of metal pre-texturing methods has been extended by a laser process using ultra-short pulses, and compared to the further optimized incumbent options such as cw laser texturing, ConiPerf, and GripMetal.

Furthermore, the range of load scenarios, the joined samples were tested in was extended to tensile-shear, peel, and tensile load. Weathering tests simulate the environmental influences typical in targeted fields of application. The polymers used were carbon-fiber or glass-fiber reinforced plastics.

The results show that high breaking tension values, typically higher than the base material strength, may be obtained. However, they also show that texturing and joining methods have to be chosen according to the load pattern, the load amplitude, and the geometry of the given application. As an outlook, a prototypical application in a real-world automotive is presented.

Keywords: Laser joining; polymer metal joining; hybrid material; metal surface texturing; ultra-short laser pulses;

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1. Introduction

With an increasing volume of CO_2 emissions over the last years, traffic contributes a large share of the emission of greenhouse gases worldwide (Fig.1). Consequently, the European Union decided to limit the carbon-dioxide emission of passenger vehicles to 95 g CO_2/km until 2021. Thus the automotive industry is working in different ways to reduce fuel consumption and therefore CO_2 emissions (Fritz et al., 2014).

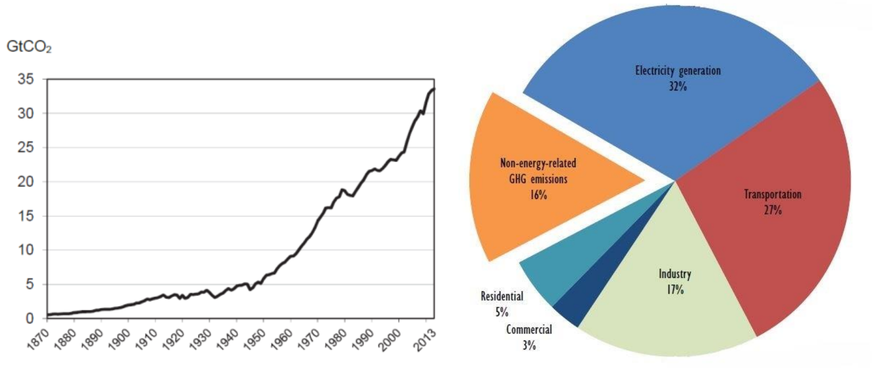

Fig. 1. left: Increase of CO_2 emissions worldwide (Carbon Dioxide Information Analysis Centre, 2014); right: Main contributors of CO_2 emissions (US EPA, 2014)

As the efficiency of combustion engines is very limited, lightweight construction is believed to be a promising option to reduce CO_2 emissions. Even for electric motors which directly do not produce any CO_2, weight reduction is necessary to increase their range to make them competitive to gas consumption motors (Eckstein et al., 2012). One major option for lightweight construction is the usage of new materials such as fiber reinforced plastics (FRP) which distinguish themselves by very high strength as well as low density. Especially in the automotive industry, more and more steel components are being replaced by FRPs. The biggest challenge with a multi-material-construction is the joining of the components. In terms of weight reduction, laser joining provides a process without the use of any additional material and is free from damaging by mechanical bonding elements. To keep up with the compound-strength achieved by traditional joining processes, a suited surface treatment of the metal component is necessary. In the metal-polymer-compound mechanical adhesion represents by far the biggest share of the adhesion (Habenicht, 2009). After texturing the metal sheet it is joined to the polymer by the laser. With laser joining it is possible to join even complex geometries with high accuracy. For this process the metal is heated up by a laser beam. The metal conducts the heat to the polymer until the latter melts up; while putting defined pressure on the samples the melted polymer floats into the structures of the textured metal. While cooling down, the polymer hardens and a mechanical interlock between the metal and the polymer is generated.

For the texturing process many options are available. After first experiences from former EU-projects “Ybridio” and “PMjoin”, the four most promising methods were chosen for further testing (Fig. **2**).

There are two mechanical texturing methods and two laser-based, thermal ones. The mechanical methods are GripMetal© and Coniperf©. GripMetal texturing is a stamping process from Nucap Industries

Inc. which forms hooks on a micro-scale out of the metal surface. Coniperf texturing, a special perforation technique from Andritz Fiedler GmbH is used to achieve openings that are ten times smaller than the metal sheets' thickness. The two thermal methods differ in the type of laser irradiation. For the first method, continuous wave irradiation, focused in a spot, is guided by scanning optics in straight lines over the joining area. The metal is heated up locally so fast that it sublimates and a small notch is created. By repeated crossing the notch gets deeper. The out-blown metal steam takes a small amount of melt out of the structure (Fig.2). The melt partly solidifies at the edge of the structure and forms an undercut. With too many repetitions the structure can be fully closed by the solidified melt. An even bigger undercut is generated if the structures are created at a defined angle. The used samples were textured by Fraunhofer-Institut für Lasertechnik. The second kind of laser-based texturing are cone-like-protrusions (CLPs; Texturing by Pulsar Photonics GmbH). It is a self-assembling structure that originates while ablating with certain parameters. No undercuts are created, but the high structure density makes it a promising method. In contrast to cw laser surface texturing (cw LST), the CLPs only occur with very special parameters. So the process window is very small and virtually no adaptions are possible. With cw texturing there are various parameters (laser power, scanning speed, repetitions, distance of the structures, angle of irradiation…) available for optimization to create a perfect structure.

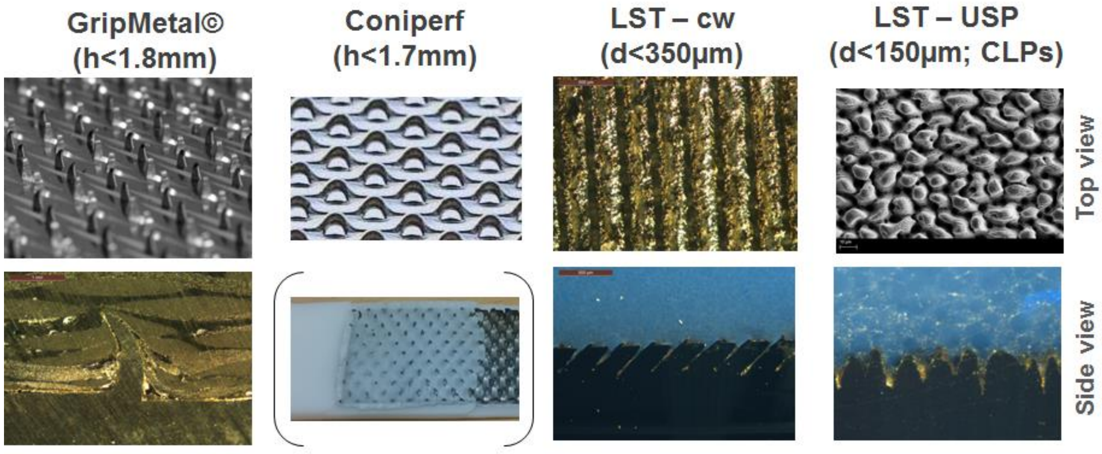

Fig. 2. Examined texturing methods. h/d: height, resp. depth of the structures

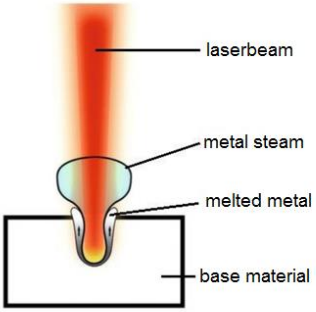

Fig. 3. Laser texturing process with cw irradiation (Brecher 2011)

2. Set-up

The basic set-up strongly depends on the transmission of laser irradiation by the polymer. There are two options:

In case the polymer is transmitted by most of the laser irradiation, the components are irradiated from the polymer side. So the laser beam transmits the polymer and is absorbed by the metal directly in the joining area (laser transmission joining, LTJ, Fig.4(left)). Then the metal conducts the heat to the polymer and it melts in the contact area.

On the other hand, if the polymer absorbs most of the irradiation it is necessary to irradiate the metal side. The laser beam gets absorbed right away on the surface but needs to be transported to the joining area through the thickness of the metal sheet (laser conduction joining, LCJ; Fig. 4(right)).

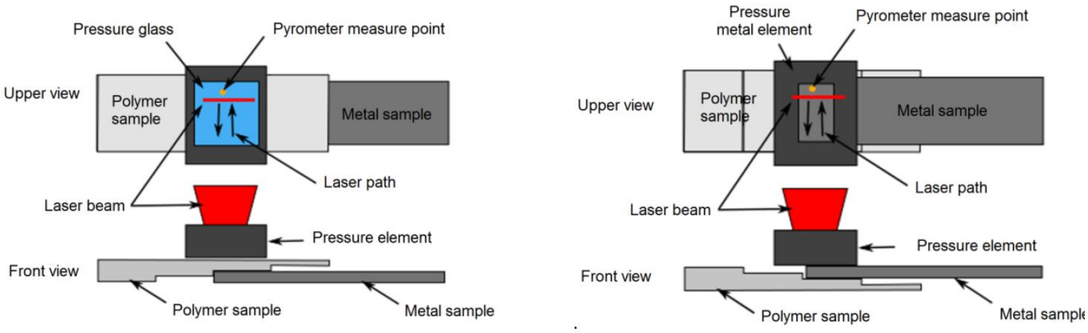

Fig. 4. Set-up for LTJ (left) and LCJ (right)

A summary of the material used in the experiments is listed in Table **1** and Table **2**. The dimensions for the metal sheets are 80x25 mm and for polymers 80x20 mm, respectively. The length of the joining area is adapted to each combination separately. The results are always normalized to the joining area to assure comparability. The largest fraction of the adhesion for laser joining is contributed by mechanical adhesion, so the different materials do not affect the adhesion that much.

The use of two different PA66 polymers stems from their availability. Carbon was used to examine the influence of endless-carbon-fibers. GripMetal is the only texture where the metal intrudes the polymer and not the other way round. That is why this is the only texture which benefits from carbon. For the others the used carbon does not provide enough matrix material to fill the structures properly.

Table 1**.** metal samples

metal	thickness	usage
1.4401	3 mm	GripMetal
1.4301	2 mm	for rest of polymer samples

Table 2. polymer samples

polymer	thickness	characteristics	Usage
PA66GF35 (natural)	4 mm	natural, transparent, stage geometry	peel tests, all Coniperf
Carbon	4 mm	52-55% carbon fiber content, PA-matrix, endless fiber, non-transparent	GripMetal (tensile-shear)
PA66GF30 (black)	10 mm	black, non-transparent	rest

The following joining tests were carried out with the LineBeam© laser from Leister Technologies AG (Fig.5). It uses a diode laser stack with optical power up to 600 W. The samples are irradiated by a line shaped beam with a length of 28 mm and feed rate between 100 mm/min and 300 mm/min.

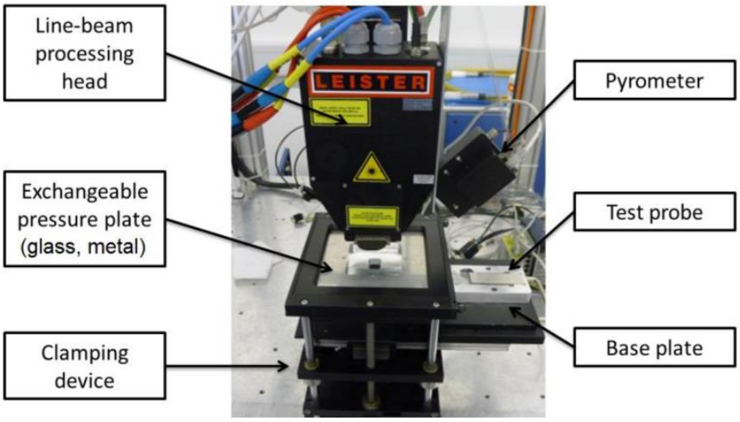

Fig. 5. Set-up for hybrid laser-joining

With climate-cycle-testing, the impact of environmental influences on the joint was investigated. The test is executed in a standard climate cycle according to IEC 68-2-38 (Fig.6) to examine the aging of the joint. The cycle is repeated three times.

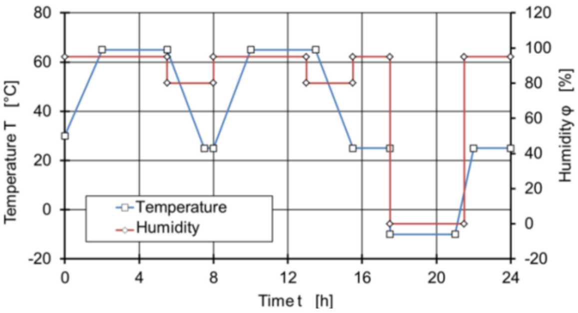

Fig. 6. Climate cycle test according to IEC 68-2-38

In a final step the joined samples were tested destructively in a tension testing machine by Zwick AG, shown in Fig.7. The size of the sample joining area is always dimensioned for the compound to break within the joining area and not in the base material. The samples are tested under tensile shear-/peel- and tensile stress (Fig.8). The breaking tension is calculated from the measured breaking-force and the size of the joining area, thus comparability is always given.

Fig. 7. Destructive testing of the hybrid samples

Fig. 8. Samples geometry for different types of stress

3. Results

Most current applications have complex load conditions. So it is important to know the behavior of joints under different types of stress. Thus, all four texturing methods were tested under tensile-shear-, peel-, and tensile-stress, with the results being assembled in Fig.9.

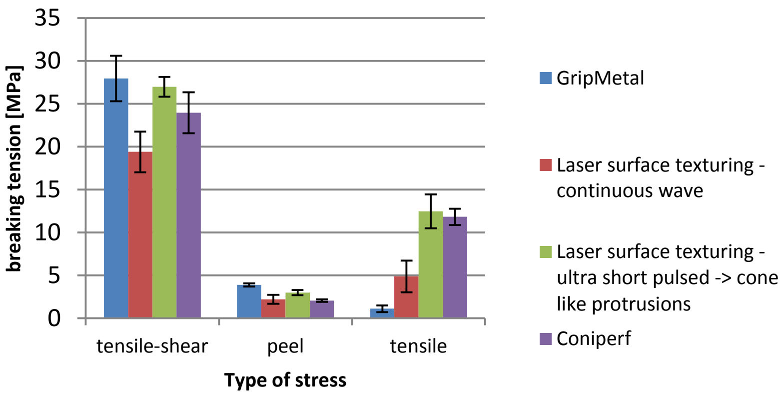

Fig. 9. Standard-tests

One major conclusion is the different behavior regarding the stress-type. All in all, the hybrid compounds withstand the highest stress loads in tensile-shear testing. Under tensile stress the breaking tension decreases, depending on the texturing method, about 50% or even more. The peel strength is lower than 15 % of the tensile shear strength. As seen in Fig.9, the proportion of the compound strength for different stress types is different for each texturing method. Especially the GripMetal samples show unusually weak results for the tensile test. In the tensile shear test, the compound's interlock equals the height of the hooks.

Because of the 90° turn of the load direction in the tensile test the interlock is only as large as the bending of the hook tips which is only a fractional amount of the overall hook height.

The apparently two best options from the diagram have also significant disadvantages:

The CLP texturing requires really long cycle times. Whereas cw texturing takes just a few seconds per square centimeter, the CLPs need a few minutes. Thus it is currently not profitable for a high volume series application.

The Coniperf method on the other hand has the restriction that it can only be used with transparent polymers. As the holes penetrate the whole metal sheet there is always direct irradiation on the polymer which, if it is non-transparent, burns immediately. Furthermore, the melted polymer flows through the metal structure and pollutes the clamping glass. So an additional cleaning process is needed after a few joined samples.

Another important aspect for a real-life application is the influence of the environment. Therefore the same join types as before were tested after being exposed to a defined climate cycle. In an elementary tensile test with PA66GF35 the strength decreases about 41 % because of accelerated aging. The polymer is the significantly weaker component in the joint so its strength decrease is in focus for climate testing. The results are summarized in Fig.10. These tests were not executed for CLP textured samples because of the long cycle times in texturing. Similarly to the standard tests, the breaking tension depends on the texturing method as well as the stress type. For the tensile shear tests all samples regardless of the texturing show a decrease in the breaking tension (14.3 % on average). For tensile- and peel-testing the results are not that clear. For each of the two stress types there is one outlier value where the breaking tension increases after the climate cycle. With accelerated aging the mechanical characteristics of the compound are getting worse so the different behavior cannot be explained. However, the standard deviation is quite large, so the results are not directly representative.

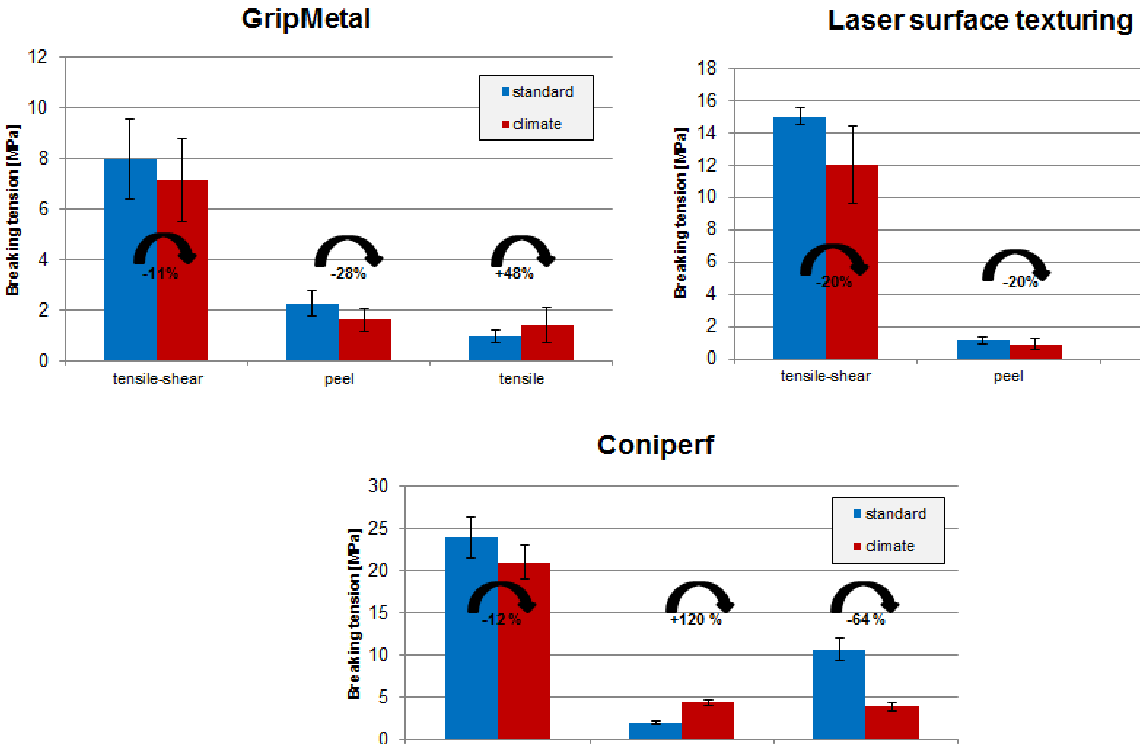

Fig. 10. Climate cycle tests according to IEC 68-2-38

4. Conclusion and project FlexHyJoin

After investigation in different projects a few texturing methods emerged to be useful for series production. The choice of the texturing method strongly depends on the application and its load condition. Samples with continuous wave laser surface texturing do not yield the highest compound strengths, however this texturing process has significant advantages such as short cycle times and low requirements towards the polymer.

Climate cycle tests do not provide clear results. All in all, a decrease of the compound strength is evident, but a few outlying values exist. The steadiest results were obtained from cw LST samples.

Every texturing method leaves room for improvement. In this survey, the cw LST turns out to be the most suitable texturing method for hybrid joining because of its low cycle times and moderately balanced compound strength regarding different stress types.

Cw LST is used in the current EU project “FlexHyJoin”, where a fully automated production cell for hybrid joining of metal and plastics is being developed. In the production cell, the whole process chain will be included, i. e. systems for texturing, induction as well as laser joining, online monitoring, and non-destructive testing (Fig.11). Thereby the whole process chain is going to be improved and adapted to series production to reach higher reliability and efficiency. FlexHyJoin is geared towards the automotive sector and deals with the production of a roof stiffener as an actual application (Fig.12).

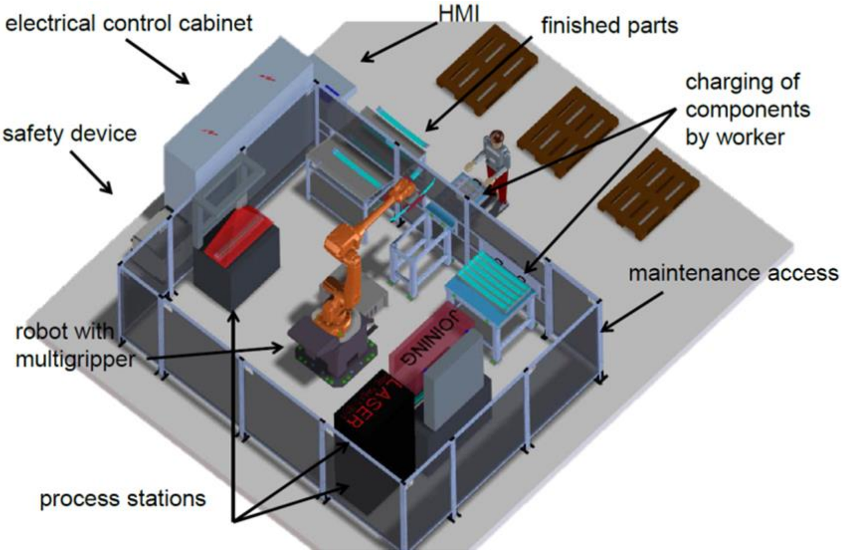

Fig. 11. production cell for FlexHyJoin (courtesy of Fill Gesellschaft m. b. H.)

Fig. 12. Demonstrator part for FlexHyJoin (courtesy of HBW Gubesch thermoforming GmbH)

The roof stiffener itself (black part) is made of glass-fiber reinforced polyamide 6. The metal parts work as a connection to the interior (middle metal sheet; joined to roof stiffener by induction) respectively the body-in-white (metal sheets on the side; joined to roof stiffener by laser).

The basic process developed in previous projects, is now to be adapted to a much more complex component and an industrial environment.

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