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# Metal meets Composite - Hybrid Joining for Automotive Applications

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**Abstract**

Especially in automotive construction the bonding of dissimilar working materials is an important requirement. The combination of different working materials, such as thermoplastic composite materials and body steels, adapted to local loads should create new opportunities for further weight reduction. The presented approach consists of a microstructuring process to generate undercut grooves on the metal surface. In a second laser based process the thermoplastic composite material is melted and by external clamping the plasticized material is pressed into the generated structures and forms after curing a mechanical interlocking between both materials.
In case of the presented PSA demonstrator a composite reinforcement bar has to be joined to a commercial vehicle door. At first suitable parameters for the surface treatment of automotive body steels P260 and XSG are presented. For the surface treatment a scanner based single mode fiber laser system is used, varying parameters like scan speed, laser power and number of iterations to generate microstructures in form of lines with undercut grooves.
Afterwards the results of a diode laser based simultaneous joining process are shown, whereby the parameters laser power and pulse duration are changed. To find out suitable joining parameters, which guarantee a homogeneous structure filling and high connection strength, flat shear tension specimen are joined and tested. The strength results are used to specify the bonding area between door and reinforcement bar to fulfill the requirements. At last all gained results are transferred to the demonstrator to join hybrid parts for crash tests at PSA.

Keywords: Joining; Hybrid Lightweight Components; Composite; Metal

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## 1. Introduction

### *1.1. Motivation*

Nowadays the automotive industry is searching for lightweight structures to slow down energy consumption of their vehicles. In recent years, the European Commission passed new laws limiting the $CO_2$ emissions of new cars. These laws require that new cars registered in the EU do not emit more than an average of 130 g $CO_2$/km by 2015 and 95 g $CO_2$/km by 2020. If the average $CO_2$ emissions of a manufacturer's fleet exceed its limit value, the manufacturer has to pay penalty payments for each registered car [European Commission, 2015].

In this context the automotive industry is increasingly interested in a smart material mix, which enables lightweight construction. To achieve this goal, car body steel is partially substituted with lighter materials. This fact is causing a large inclusion of non-metallic materials such as plastics. Fiber reinforced plastics are of special interest due to their high lightweight potential. A direct and firm bond between metal and plastic fails due to their chemical and physical differences. There are different process chains, which enable a strong joint between plastic and metal like adhesive bonding or the laser assisted approach shown in Fig. 1.

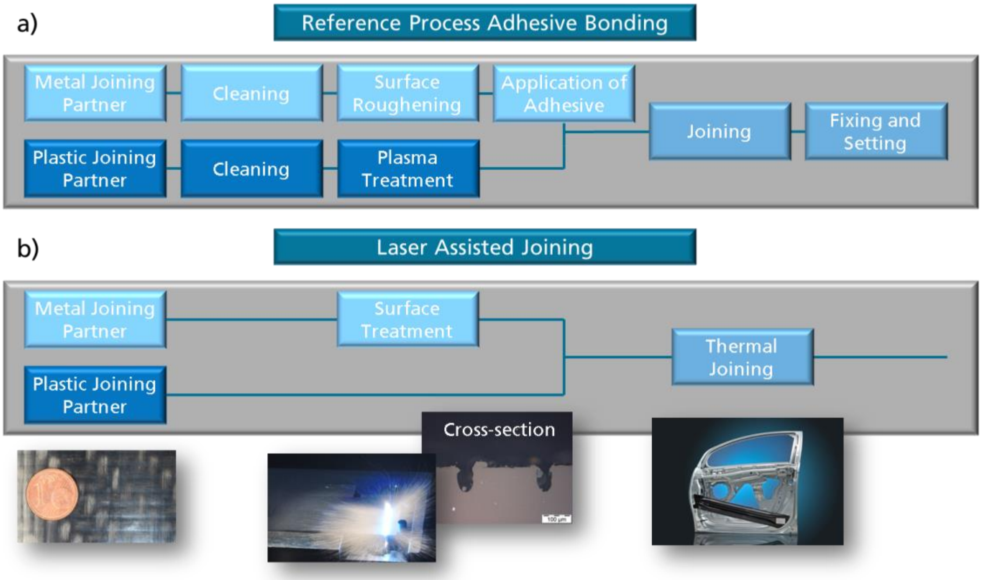


Fig. 1. comparison of two process chains for hybrid joints: (a) adhesive bonding; (b) laser assisted joining

The process chain of adhesive bonding takes a lot of steps to achieve a firm bond like cleaning operations, surface treatment of metal and plastic, application of adhesive and afterwards fixing and setting of the components. In comparison to adhesive bonding, the laser based approach consists only of two process steps, a surface treatment process of the metallic joining partner and a thermal joining process. Other advantages of the laser assisted process chain are the omission of additional material like glue and that the bond is not subject to ageing.

*1.2. Laser based process chain and evaluated PSA demonstration part*

The laser based approach is depicted in Fig. 2 and consists of a microstructuring process to generate undercut grooves on the metal surface. In a second laser based process the thermoplastic composite material is melted and by external clamping the plasticized material is pressed into the generated structures and forms after curing a mechanical interlocking between both materials [Holtkamp, 2012].

The application of high a speed laser microstructuring process of the metal surface is a productive way to realize fast cycle times needed for efficient production processes in the automotive industry. The beam movement is realized by a galvometric scanning system, which is capable of scanning variable structure patterns at high speed. Especially stress peaks in the connection area can be avoided, if the orientation and density of the microstructures are designed to deliver a homogeneous stress profile. Based on a combination of sublimation and melting, the process speed is much faster compared to conventional structuring processes [Engelmann, 2013]. The evaporation pressure created by the high laser intensity in the middle of the microstructure ejects the surrounding melt out of the structure bottom towards the surface. The structuring process is repeated to achieve an undercut structure since the generated melt recasts not only on the surface but also on the border of the structure.

The subsequent thermal joining process is realized by conductive joining. The metal surface is irradiated with a laser beam and by heat conduction the plastic is molten at the interface between plastic and metal. The plasticized material expands and is pressed into the generated structures by external clamping. For a firm bond, the plasticized material has to flow into the generated structures, which have an undercut geometry, and to harden there. The described laser assisted process chain is flexible and can be adapted to different thermoplastic materials and metals, which are mandatory for various lightweight applications [Engelmann, 2015].

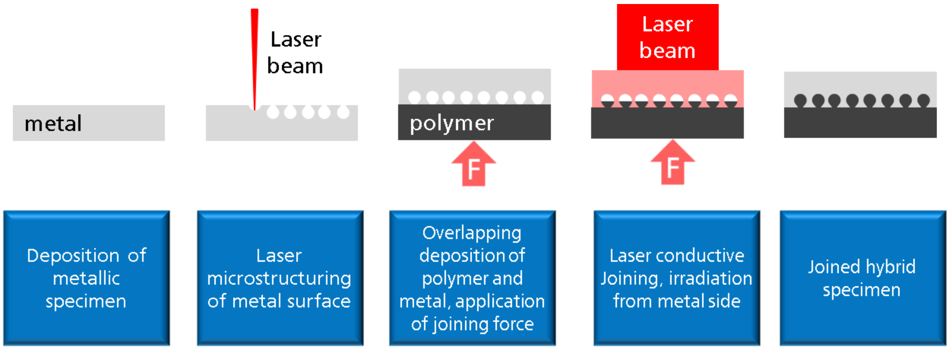


Fig. 2. laser based process steps: Microstructuring of metal surface and conductive joining from metal side

The PSA demonstrator presents a hybrid joint between a metallic car door and a composite reinforcement bar. The reinforcement bar consists of a biaxial orientated glass fabric sheet, which is embedded in a PA6.6 matrix. The thickness of the material is 1.5 mm. There are three joining areas between the metallic door and the reinforcement bar. The metal material of areas A and B is P260 (Hinge side, thickness 1.76 mm), the second material for the third joining area C is XSG (Internal panel side, thickness 0.67 mm). The joining task comprising of the three joining areas between door and reinforcement bar is depicted in Fig. 3.

At first suitable parameters for the surface treatment of automotive body steels P260 and XSG are evaluated. Afterwards the composite material is joined by heat conduction to the two body steels by a diode laser based simultaneous joining process, whereby the parameters laser power and irradiation time are changed.

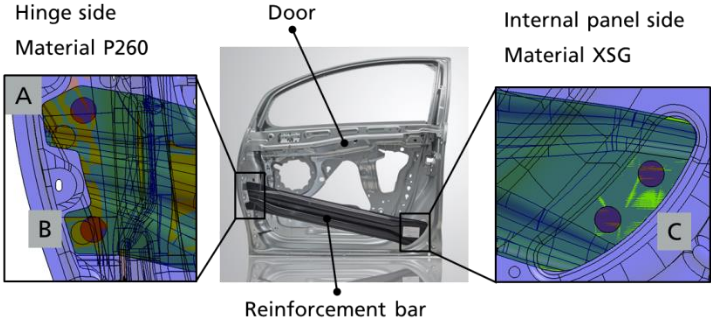


Fig. 3. PSA demonstration part with two joining areas A and B on hinge side (material P260) and one joining area C on internal panel side (material XSG)

To find out suitable joining parameters, which guarantee a homogeneous structure filling and high connection strength, flat tensile shear specimens are joined and tested. The tensile shear strength results are used to specify the bonding area between door and reinforcement bar to fulfill the requirements.

## 2. Experimental set-up

Utilized laser source for microstructuring process is a water cooled IPG Photonics 1000 W single-mode cw fiber laser, operating at 1064 nm wavelength. The beam source is portable and of simple automation, therefore, it can be integrated on different machines, machining centers, robots, etc. Given the high quality of the laser beam ($M^2 < 1.07$) the system is ideal for joining, micro-machining, cutting and welding applications. The laser radiation is deflected by an Intelliscan 25 galvanometric scanner to achieve different structure patterns. By the use of a focusing F-theta optics with a focal length of 330 mm a focal radius of 20 µm is created. The metal specimens are positioned in a device to achieve reproducible results. The complete system set-up is depicted in Fig. 4.

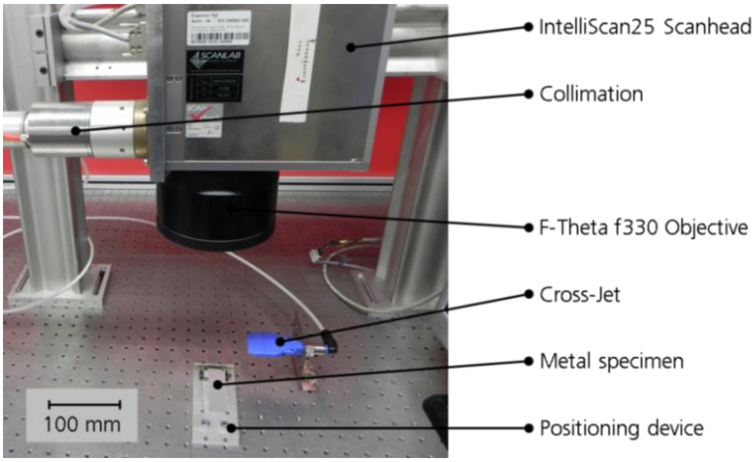


Fig. 4. system set-up for microstructuring process

The generated microstructures have been analyzed microscopically by cross sections. Therefore the samples have been embedded in resin, grinded and polished.

The laser system used for the joining process is a Laserline GmbH LDM 3000-100, 3000 W continuous wave diode laser, operating at 1018 nm wavelength. The laser beam is guided through an optical fiber into a zoom homogenizer optics device (Laserline GmbH) with a focal length of 250 mm shown in Fig. 5. The zoom optics allows forming the laser beam into a rectangular shape. The spot size can be varied flexibly between 5x5 mm² and 30x16 mm². In order to apply pressure and fix the sample arrangement a pneumatic clamping device with a specimen fixture is used. Plastic and metal specimens are placed overlapping inside the fixture and pressed with the pneumatic lifting cylinder against a clamping frame. The specimens are irradiated through the clamping frame from the metal side. A cross-jet with pressured air prevents the optics from contamination with process emissions.

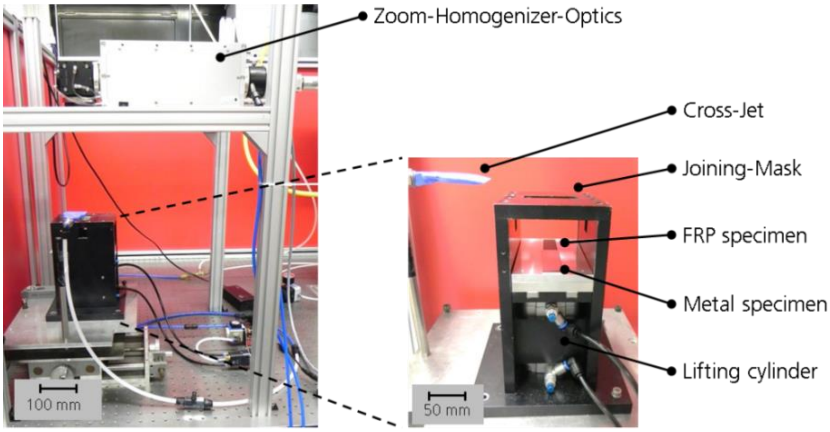


Fig. 5. system set-up for laser based conductive joining process

The mechanical properties of the welded samples are tested with a multi-purpose testing machine Z100 from Zwick GmbH & Co. KG. For tensile shear testing a tensile force is applied parallel to the joining area and the breaking force is measured according to DIN 527-1. The samples are fixed between the clamping jaws in a 50 mm distance (Fig. 6(b)). The testing speed is set to 50 mm/min. For each parameter five samples are tested. The 6th sample is grinded and polished to microscopically analyze the structure filling and to show possible decomposition of the matrix material caused by a too high joining temperature. The dimensions of the tensile shear test specimen are depicted in Fig. 6(a), the overlap between plastic and metal is 16 mm.

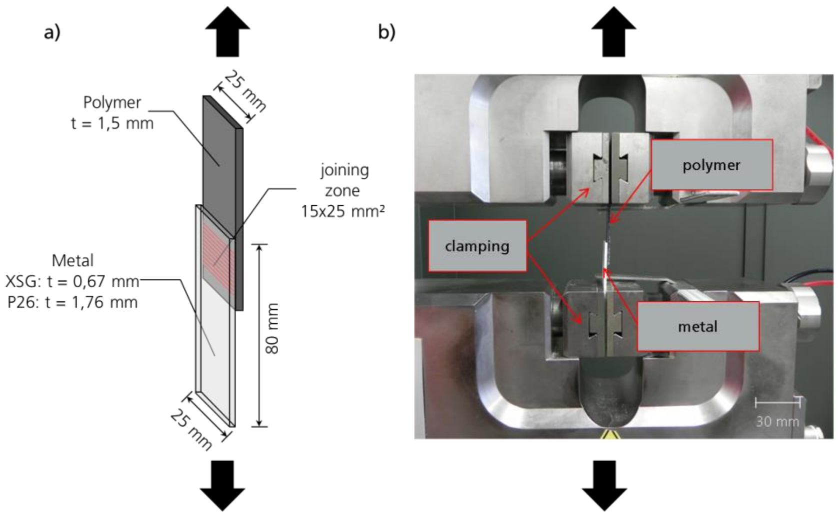


Fig. 6. (a) dimensions of tensile shear test specimens; (b) welded sample fixed for tensile shear test in testing machine

## 3. Results

### *3.1. Evaluation of the microstructuring process for P260 and XSG*

The generated structures are analyzed by cross sections to measure the structure depth and the undercut ratio. The undercut ratio is defined as the relation between the biggest width of the microstructure b2 and the width of the opening cross section b1 shown in Fig. 7(b). The microstructure has an undercut groove, if the ratio is above one. For a high connection strength a sufficient structure depth and undercut ratio is necessary [Rösner, 2014; Schricker, 2014]. These two parameters can be influenced by varying microstructuring parameters like the number of repetitions, which is shown in Fig. 7(a). A higher number of repetitions lead to a deeper structure and a bigger undercut groove, if the other structuring parameters are kept constant. If the number of iterations is too high, the microstructure is partially sealed, which leads to a lower connection strength due to the smaller joining surface.

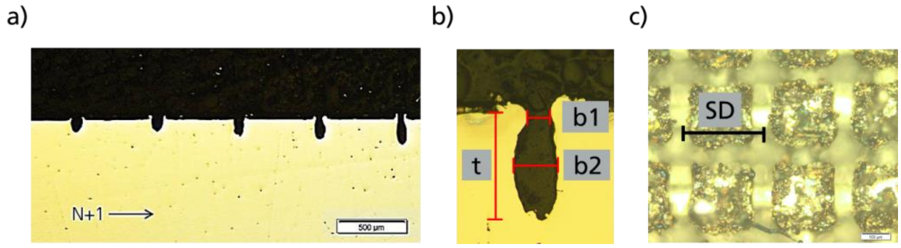


Fig. 7. (a) formation of the undercut groove by an increasing number of repetitions; (b) analysed geometric parameters of microstructures; (c) generated pattern on metal surface in form of crossed microstructures

For the analysis of the geometric parameters the laser power is varied, while the other structuring parameters for both body steels have been kept constant with:

- Scan speed v=10 m/s
- Number of repetitions N=4
- Structure distance between crossed structures SD=300 µm (see Fig. 7(c))

At first the microstructuring process for P260 body steel is evaluated to find out suitable parameters for the process to generate deep structures with an undercut groove. The analysis of the geometric parameters depicted in Fig. 8(a) has been done for four different laser powers (800, 850, 900 and 950 W). The increase of the laser power from 800 W to 850 W leads to a deeper structure with a bigger undercut groove. If the laser power is raised to 900 W and 950 W, the intensity is too high and the microstructures are sealed again due to a bigger melt volume, which solidifies on the opening cross section (b1). This leads to a decrease of the structure depth and undercut ratio. The structuring parameter for P260 is set to 850 W laser power for the preparation of tensile shear test specimen, the corresponding cross-section is shown in Fig. 8(b).

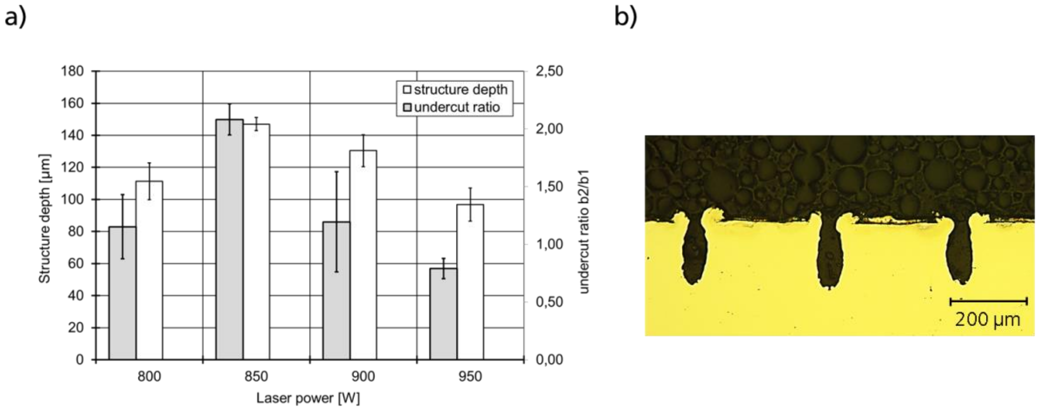


Fig. 8. (a) analyzed geometric parameters for different laser powers for P260; (b) cross section of microstructures for chosen parameter (laser power 850 W)

As the next step, suitable structuring parameters for XSG are evaluated. The results of the microscopic analysis of the geometric parameters are shown in Fig. 9(a). The analysis has been done for three different laser powers (700, 750 and 800 W). In comparison to the results of P260 body steel, the variation of laser powers shows a minor influence on the geometric parameters for XSG body steel. For a laser power of 800 W, the highest undercut groove is achieved with a comparable structure depth to the other laser powers. The structuring parameter for XSG is set to 800 W laser power for the preparation of tensile shear test specimen, the corresponding cross-section is shown in Fig. 9(b).

a) b)

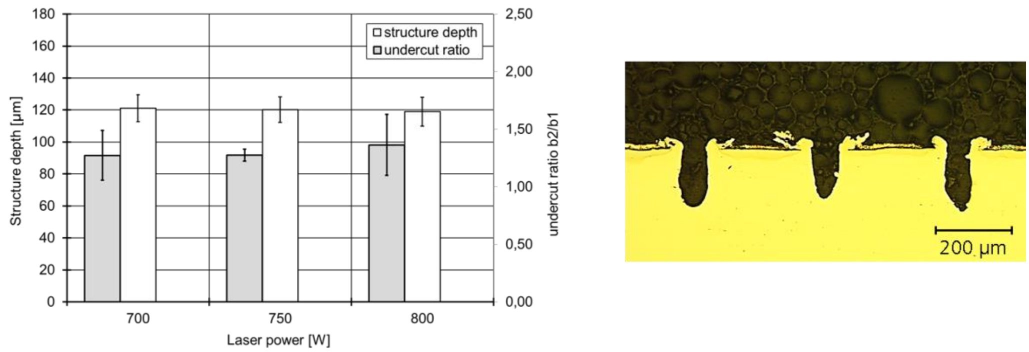


Fig. 9. a) analyzed geometric parameters for different laser powers for XSG; (b) cross section of microstructures for chosen parameter (laser power 800 W)

### *3.2. Evaluation of conductive joining process between composite and P260/XSG*

In order to achieve a strong and durable connection between composite and both body steels, the right joining parameters have to be chosen. It is necessary to use sufficient laser power to melt enough material to fill the structures and create an interlocking. On the other hand too much laser power can lead to a decomposition of the plastic material, because the temperature at the interface exceeds the degradation temperature of the matrix material (PA6.6). This leads to a formation of bubbles in the joining zone. These bubbles provide weak spots for cracks and reduce the long term stability of the connection. The decomposition of the material can be detected through smoke and odor development and also trough bubbles visible in cross-sections.

The joining process is carried out via simultaneous irradiation by zoom homogenizer optics. The spot size is adapted to the structured area of the body steels (10x25mm²). The process parameters are chosen via variation of laser power and irradiation time.

At first the joining parameters for P260 body steel are evaluated. The samples are irradiated with two different laser powers (1270 and 1710 W) and three different irradiation times (1500, 2000 and 2500 ms). The resulting tensile shear strengths are depicted in a bar diagram, shown in Fig. 10(a). The joining parameter is chosen by high strength of the connection with low standard deviation and no decomposition of the material in the joining process. The highest tensile shear strengths can be achieved with 1710 W laser power and irradiation times of 2000 ms and 2500 ms. A cross section of the higher irradiation time shows a formation of bubbles and therefore a decomposition of the polymer matrix material (see Fig. 10(b), top picture, red marked spots). This parameter is not viable for a durable connection. A cross-section of the lower irradiation time does not show this kind of decomposition (see Fig. 10(b), bottom picture).

As the next step, suitable joining parameters for XSG are evaluated. In comparison to P260 a lower intensity is needed to avoid damage of the zinc coating on XSG body steel. If the intensity is too high, the zinc coating is fused and destroyed during the joining process, which must be avoided.

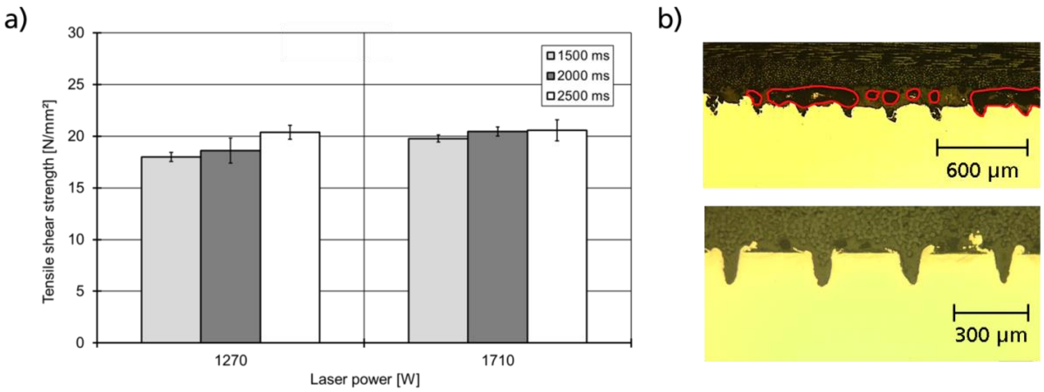


Fig. 10. (a) tensile shear testing results of P260; (b) cross sections of joined specimens with defects (1710 W laser power and 2500 ms irradiation time (top)) and without any defects (1710 W laser power and 2000 ms irradiation time (bottom))

The samples are irradiated with a laser power of 575 W and three different irradiation times (2000, 2500 and 3000 ms).The results of the shear tension test are shown in Fig. 11(a). Using an irradiation time of 2000 ms leads to a tensile shear strength of 16.12 N/mm². If the time is raised to 2500 ms the tensile shear strength is increased to 17.8 N/mm². Due to the longer interaction time between laser beam and metal surface, more plastic material is molten at the interface leading to a homogeneous structure filling with matrix material, depicted in Fig. 11(b). If the irradiation time is raised to 3000 ms, the tensile shear strength is decreased. Caused by the longer irradiation time, the temperature at the interface exceeds the degradation temperature of the matrix material and defects occur. These defects in form of bubbles decrease the connections strength due to a smaller bonding area.

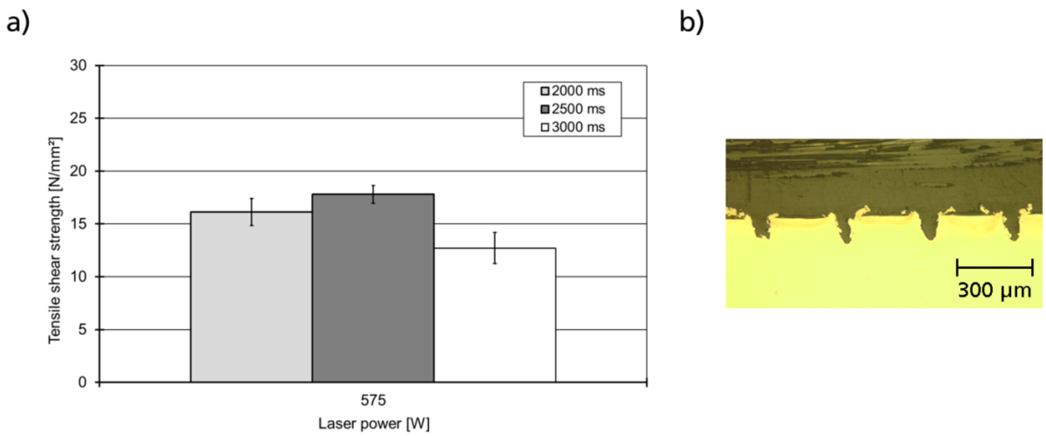


Fig. 11. (a) tensile shear testing results of XSG; (b) cross sections of joined specimen without any defects (575 W laser power and 2500 ms irradiation time

The value of tensile shear strength is higher for the P260 combination (20.47 N/mm²) compared to the XSG combination (17.8 N/mm²). The main reason for this difference can be explained by the higher stiffness of P260 body steel compared to XSG body steel. The tensile shear test causes a higher bending moment, if the stiffness of the metal or plastic material is reduced. This bending moment causes peel stress in the bonding zone, which decreases the connection strength significantly.

## 4. Summary and Outlook

The described laser based process chain allows a flexible and fast microstructuring and conductive joining process. Compared to adhesive bonding, the laser based approach enables the joining of dissimilar materials without additional material and a reduction to only two process steps. The flexibility of the processes allows the hybrid joint between the composite reinforcement bar and the body steels P260 and XSG.

For both body steels suitable structuring parameters were evaluated to create structures with a high depth and an undercut groove. Within the subsequent laser conductive joining process, high connection strengths due to a high structure filling rate were achieved. The tensile shear strength for the connection between composite and P260 is 20.47 N/mm² and 17.8 N/mm² for XSG and composite.

These values are sufficient for the requirements given for the three joining areas A, B and C regarding tensile shear strength. The next step will be the microstructuring of these areas with the evaluated parameters and the conductive joining of the reinforcement bar to the door. Afterwards the joined doors will be evaluated by a crash test at PSA.


## Acknowledgements

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