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# Laser direct joining of metal-polymer hybrid connections using a single beam source and processing station

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**Abstract**

Laser direct joining of metals and plastics is a promising process for producing strong and reliable joints for lightweight hybrid structures without the need for adhesives, primers or mechanical fasteners. Commonly this process consists of two separate steps using at least two processing stations: the surface of the metal part is textured to achieve an increased surface roughness and improved mechanical interlock between the components. In another step, the thermoplastic components or the matrix of thermoplastic fiber reinforced composites are selectively heated to allow the melt to flow into the prepared metal structures. In this work, a new method is presented that combines highly efficient laser surface texturing of metallic parts and the selective laser heating of the joining zone in a transmission joining process using a single laser beam source running in different operation modes. This enables a very compact and cost-efficient processing station.

Keywords: Laser direct joining; metal-polymer connections; surface texturing; transmission joining;

## 1. Introduction

Hybrid structures made out of metal and plastics or polymer-based composite components are widely used in aerospace, automotive or railroad applications due to their light weight and high strength, Weidmann 2020. In electrical, medical or household applications these materials are often combined to ensure the desired thermal, electrical, structural, optical or haptic properties while using the geometrical flexibility and low cost of plastics manufacturing processes, Bula 2020. Depending on the application, conventional joining methods to combine metals and polymers or polymer-based fiber-reinforced composites include adhesive bonding,

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riveting or screwed connections. The use of adhesive bonding is often limited by limited strength and long curing times and involves harmful chemicals in adhesives, primers or cleaning products, Lambiase 2018 and Jung 2013. Mechanical fasteners induce unwanted stress concentration at the required through-holes, Wang et al 2023, and can be difficult to install depending on the accessibility of the joint area. Laser direct joining of metals to polymers can be an attractive alternative for many applications that require a strong and reliable bond between thermoplastic and metal components, Katayama 2008 and Klotzbach et al 2017.

The process consists of two main steps: In a first process the surface of the metal component is pretreated using laser radiation. This increases its surface area and therefore the interaction zone between the metal and the plastic part. Furthermore, suitable surface geometries can generate undercuts and geometric interlocking, leading to significantly increased load-bearing capacities, Rodriguez-Vidal 2016. In a second step the two components to be joined are brought into direct contact and the interface between the two parts is selectively heated using laser radiation. Depending on the optical properties of the polymer part this can be achieved by irradiating the metal part and relying on heat conduction to melt the adjacent polymer part or by directly irradiating and heating the structured surface of the metallic component at joint interface through a sufficiently transparent polymer part in a laser transmission joining process, Huang 2022.

In this work we present a new approach to combine both of these processing steps into a single, compact and cost-efficient processing station as shown in Fig. 1 c), performing both the structuring and the transmission joining process by using the same single-mode fiber laser beam source.

## 2. Experimental setup

The experimental setup used in this study consists of a continuous wave (cw) single-mode ytterbium fiber laser with a maximum power of 700 W and a wavelength of 1070 nm, a galvanometer scanner equipped with application-dependent F-theta scan lenses and an electromechanical clamping device as shown in Fig. 1.

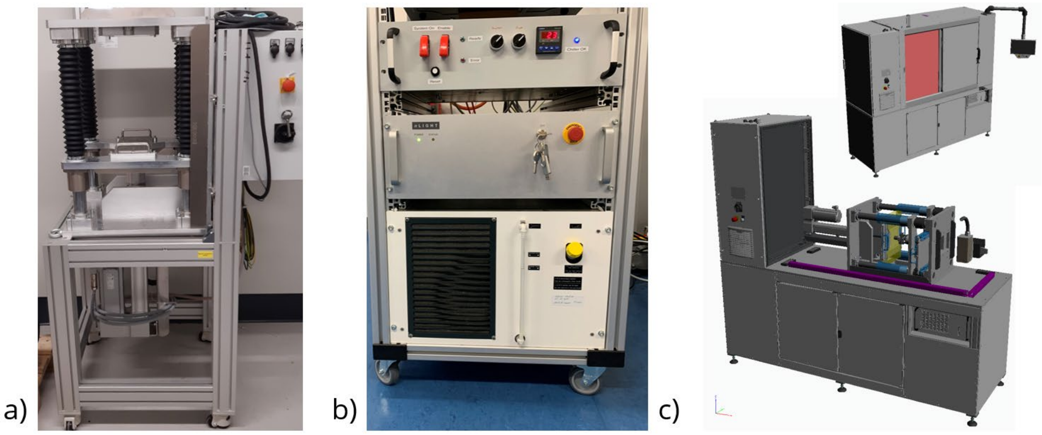



Fig. 1. (a) Electromechanical clamping device; (b) Yb-fiber laser with fast modulation capability; (c) as used in this study and concept for an integrated processing station.

The beam source is used in different operation modes for the two processing steps: In the transmission joining process the laser is operating in continuous wave mode and the scanning path generated by the galvanometer system is optimized to achieve a homogeneous temperature distribution in the joining zone. In contrast, the laser surface structuring process is performed using the fast power modulation capabilities of the beam source to improve the structuring efficiency.

The electromechanical clamping device is used to perform both processing steps in different working distances. The surface structuring of the metallic part is performed in the focal plane, achieving spot diameters of down to 24 µm. The transmission joining process is performed out of focus, with realized spot sizes in the order of 2 to 3 mm and fast scanning speeds, to achieve homogeneous temperature distributions and to avoid local thermal degradation of the plastic parts. The clamping device is furthermore equipped with a displacement measuring device and a load cell, to enable displacement- and joining-force controlled processes.

## 3. Results

Using the modulated operation mode, a highly efficient, fast and cost-efficient structuring process can be realized. The beam source applied in this study features a maximum modulation frequency of 100 kHz and rise and fall times of approximately 2 µs, Kliner et al 2018. With these parameters pulse durations in the µs regime and pulse frequencies in the order of tens of kHz can be achieved. In conventional short- and ultrashort-pulsed laser ablation processes using pulse durations in the femtosecond, picosecond or nanosecond regime, significant amounts of the materials are vaporized. The µs-pulses used in this study lead to the creation of a keyhole, with a limited amount of vapor and a much greater amount of melt. The keyhole depth is thereby dependent on the scanning speed. When the laser power is cut off, the vapor pressure collapses, leading to a disturbed equilibrium between the recoil pressure and the surface tension at the surface of the melt pool. This leads to a very efficient melt expulsion from the interaction zone, Schkutow 2022. When compared to a cw process without power modulation, the increased melt expulsion leads to cleaner cavities with reduced burrs and a smaller heat affected zone, since the heat transfer from the melt to the surrounding material is greatly reduced as shown in Fig. 2.

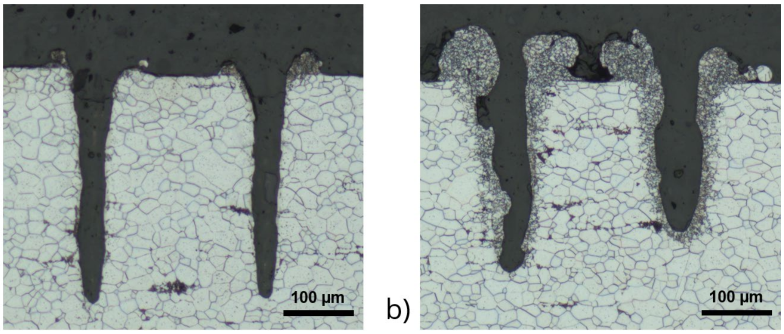
a)



Fig. 2. (a) Structures created in DC04 steel by modulated cw-radiation; (b) and continuous wave laser radiation. Processing parameters: Scanning speed: 4 m/s, number of successive irradiations: 4, cw-power: 700 W, modulated peak power: 700 W, duty cycle: 71.4 %, resulting average power: 500 W, pulse frequency: 10 kHz.

Using this structuring process, a high productivity of more than 5 cm²/s at a hatching distance of 375 µm was achieved. The bond strengths between Polycarbonate and DC04-Steel and EN-AW7075 aluminum were 23 MPa and 25 MPa, respectively. The quality of the created joints was investigated in metallographic cross-sections, showing almost completely filled cavities and only minimal air bubbles trapped in the deepest structures, as shown in the example in Fig. 3, showing an exemplary cross-section through a joint between DC04-steel and Polyamide 6.

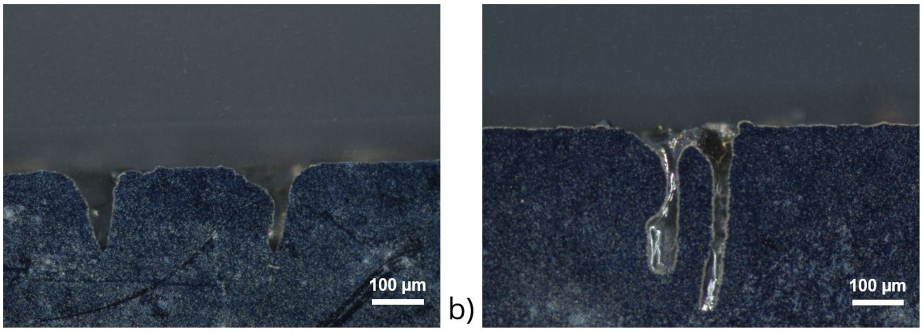
a) b)



Fig. 3. (a) Cross-section through joint between Polyamide 6 and DC04 steel showing good filling of the generated cavities by the molten polymer without visible thermal degradation; (b) and only small air bubbles trapped in deep structures after solidification of the melt.

## 4. Summary and Conclusion

By applying continuous-wave and modulated operation modes to a single-mode ytterbium fiber laser a very compact and cost-effective processing station for the creation of metal-polymer hybrid connections by laser direct joining can be created. Laser surface structuring using modulated cw-radiation was found to be an attractive alternative to commonly applied short-pulsed or continuous wave laser radiation. High joint strengths were achieved in position- and force controlled joining processes using an electromechanical clamping device.

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