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Laser direct joining of metal-polymer hybrid connections with glass fiber reinforced high-performance polymers

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Abstract

Hybrid polymer-metal parts gain popularity in the industry, for example for lightweight structures or parts with combined material properties. In order to join metals and plastic laser direct joining is the process to choose, leading to strong and reliable joints. Adhesives, primers or mechanical fasteners are unnecessary in this process, allowing also for application in medical industry. Laser direct joining of metals and polymers is based on two processes. To achieve a good mechanical bond between the parts, the surface of the metal part is structured in a first step. In the second step, the polymer is heated in order to allow the melt to flow into the prepared metal structures. This becomes increasingly challenging when using the high performance polymers usually preferred in the industry with high fiber reinforcement rates. Process optimizations lead to solving challenges such as homogeneous heating, air enclosures in the structures and surface defects.

Keywords: Laser direct joining; metal-polymer connections; laser transmission weldig; high performance polymers

1. Introduction and Principle of Laser Direct Joining

Metal-plastic composites and hybrid structures are gaining importance in a variety of technical applications. These hybrid parts offer significant advantages in the field of lightweight construction, particularly within the mobility sector (Rauschenberger et al.). Furthermore, the integration of metallic and polymer components enables the precise customization of mechanical, electrical, thermal, chemical, and tactile properties of products (Lamberti et al.). This combination enhances design flexibility and facilitates the use of established manufacturing techniques, providing greater creative freedom than monolithic components. Numerous joining methods exist for the fabrication of such hybrid joints; among these, laser direct joining is particularly noteworthy due to its rapid joining times and the absence of additional materials. In contrast to mechanical fastening methods that rely on rivets or screws, which require through holes that can compromise structural integrity and lead to undesirable stress concentrations, laser direct joining enables a more streamlined and efficient assembly process. (Rösner et al.)

The operational principle of laser direct joining is comprised of two main steps. Initially, surface structuring of the metallic joining component is conducted, thereby enhancing the interaction area between the metal and thermoplastic elements. The application of specific structural configurations facilitates additional mechanical interlocking between the components. In order to achieve the melting and vaporization of metals, lasers with high energy densities, often short-pulsed laser systems are used (Henrottin et al., Thoss et al.). These systems are characterized by extremely high peak power outputs during short pulse durations in the range of femtoseconds to nanoseconds (10^-15 s to 10^-9 s). Alternatively, continuous-wave laser systems can be utilized for surface structuring in a remote cutting mode (Thoss et al.). In this method, a laser beam, with power ranging from several hundred watts to a few kilowatts, is rapidly directed over the metal surface. The high scanning

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speed induces rapid fluctuations in vapor pressure and surface tension at the molten pool, facilitating efficient melt expulsion and high ablation rates. Nonetheless, this technique is typically limited to simpler, primarily linear scanning patterns and often necessitates multiple passes to achieve the desired depth of structuring, whereas short-pulsed laser systems can be employed for nearly all relevant materials.

In the second step, the thermoplastic component is clamped to the structured metallic counterpart and subjected to heating within the joining zone, reaching temperatures within the melting range of the polymer. The melt flows into the surface structures, subsequently solidifying within these structures, thereby establishing a positive connection. Two distinct process variants are conventionally employed for the heating of the material, which are depicted in Fig. 1. One such method is transmission joining, in which the metallic surface is irradiated through the plastic component. As in laser transmission welding, the plastic has to be transparent for the welding laser, thereby limiting the possible materials to those with suitable optical properties. The advantage of this process is the direct irradiation of the joining area, leading to a locally limited heat input. In heat conduction joining, the second process variant, the back of the metal component is irradiated and the joining zone is heated exclusively by thermal conduction (Rauschenberger et al., Rösner et al.). As the process is dependent on the wall thickness and geometry of components, it is associated with higher losses (Schricker et al.). Nevertheless, when compared to alternative heat sources for direct joining processes, the heating is limited to a small area and precisely controllable.

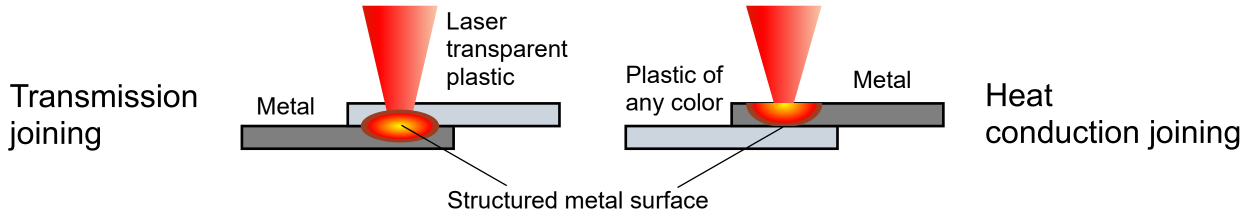

Fig. 1: Processing principle of laser direct joining

Transmission joining offers certain advantages over heat conduction joining, such as greater form freedom for the metallic part and the direct irradiation of the joining area. However, its application is constrained by the optical properties of the plastic. The objective of this research was to expand the range of joinable plastics. Polyphenylene sulfide (PPS) is a high performance polymer that is frequently utilized in the automotive industry due to its exceptional mechanical and chemical properties. Despite its potential benefits for lightweight construction in industry, laser direct joining of PPS and metal is not without its challenges, including its transmission and tendency to burn when exposed to localized overheating due to low thermal conductivity.

2. Materials and Methods

Experiments were conducted to investigate the bonding of steel (Cr-Ni-steel 1.4301) and aluminium (Aluminum alloy EN AW 7075) with PPS (Celanese Fortron 1140L4 SF3001) with 40 wt % glassfiber and a thickness of 1 mm. The transmission of this polymer at the welding laser wavelength is 10.5 %.

Surface structuring of the metallic samples was performed using a continuous-wave ytterbium-fiber laser in fast modulated operating mode. The laser power was alternated between 700 W and 0 W with a pulse frequency of 30 kHz and a duty cycle of 50 %, resulting in pulse durations of approximately 16.7 µs, rise and fall times of around 2 µs and an average power of 350 W. A galvanometer scanner system with a 167 mm F-Theta scan lens, resulting in a spot diameter of around 24 µm, was applied to create a 90° cross-type hatching pattern with a hatch distance of 267 µm. The hatch pattern was rotated by 45° with respect to the loading direction in the subsequent overlap-shear test. The combination of a relatively fast applied scanning speed of 900 mm/s and the modulated laser operation results in highly dynamic melt pool-vapor interactions and the formation of periodic melt expulsions and different sized surface features along the scanning tracks. Fig. 2 shows a scanning electron microscope image of the resulting irregular, rugged surface with a high roughness, many undercuts and surface features reaching above the initial surface of the sheet.

For laser beam joining, a diode laser with a wavelength of 980 nm was utilized. For the different material combinations, the power was adjusted between 180 W and 300 W cw. Since first tests with a beam diameter of 3.5 mm did not lead to durable connections between the materials without burning the polymer, a Midel Photonics beam shaping element was inserted into the optics setup in order to achieve a donut beam shape (Fig. 3). With this beam shape the energy distribution in the joining area gets homogenized, leading to minimized risk of surface burns as well as less thermal degradation in the polymer. Scanning speeds between 30 mm/sand 60 mm/s and a hatch distance of 1.5 mm were used with different amount of irradiation cycles (1 to 12).

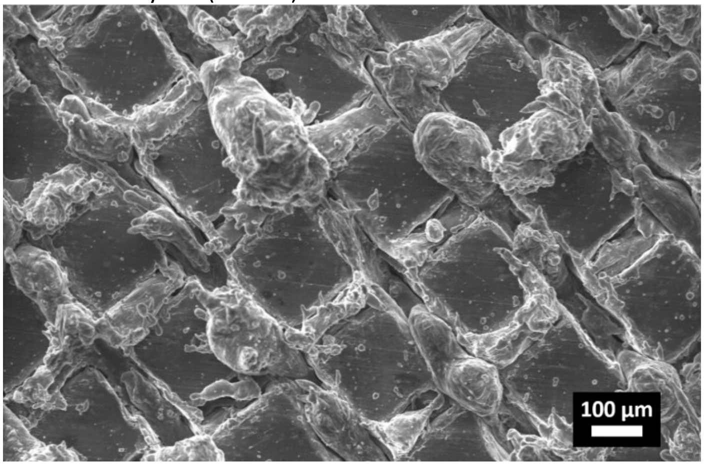

Fig. 2: Exemplary rough surface structure of laser treated aluminum (EN AW-7075) sheet

Fig. 3: Optical setup for laser beam joining with integrated Midel Photonics beamshaping optic

After joining, the hybrid structures were evaluated by conducting tensile strength tests. Due to the varying failure criteria, such as failure of the bond itself or the rupture of the polymer adjacent to the bond in various patterns, an alternative approach was employed. Rather than calculating the tensile strength or maximum shear force, additional polymer-polymer welds were prepared. A comparison was made between the strength of the hybrid connection and that of laser plastic welding bonds, which are standard in industry. As a joining partner in the plastic welding process the same PPS material with a laser absorbing additive (carbon black) was utilized.

3. Results and Discussion

Durable connection of the hybrid components were achievable for all material combinations without burning the surface of the polymer or the formation of visible thermal degradation in the material. In case of the PPS-aluminum combination a silicone mat beneath the metal was used during the laser beam joining in order to minimize the heat transfer into the utilized aluminum clamping device. The insulating layer decreases the power requirement and thus ensures the homogeneous melting of the polymer at the contact area without exceeding the degradation temperature at the surface of the polymer. As can be seen in Fig. 4 with no material combination the bond opened completely in the tests. Fig. 5 shows, that in contrast to the benchmark polymer-polymer weld, nearly the equivalent maximum force was applicable to the polymer-metal hybrid connections. Upon microscopic evaluation of the torn specimen a good infiltration of the polymer into the metallic structure can be observed (Fig. 6), which is an additional positive indicator for a very good connection.

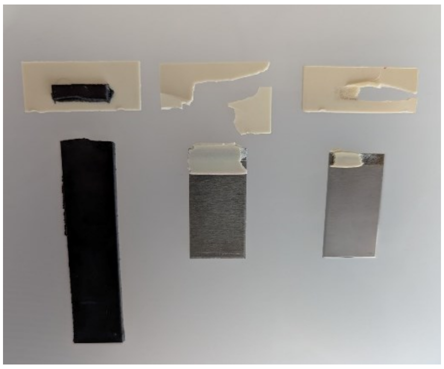

Fig. 4: Test specimen after tensile strength test

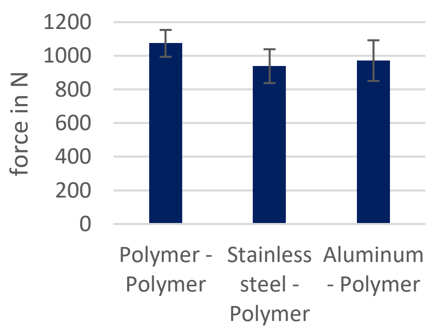

Fig. 5: Tear force in N of different material combinations

Fig. 6: Microscope image of polymer infiltration into metallic structure

4. Summary and outlook

The experimental tests demonstrated that the laser direct transmission joining of high performance polymers (PPS) and metals (stainless steel and aluminum) can be achieved through the strategic structuring of the metal, precise choice of parameters and beam properties, even when the polymer exhibits properties that pose a challenge, such as a high glass fiber content and low transmissivity. A comparison of the strength of these joints to an industrial standard process for joining polymers, laser plastic welding, reveals that the hybrid bonds nearly reach the welding strength. The results of this study show that the process is suitable for industrial use as common high performance materials can be bonded successfully. In order to broaden the range of applications in the industry, in the next step additional metals like copper will be tested. This will result in the addition of further material combinations to the existing portfolio and new opportunities for innovative, hybrid products.

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