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Advanced laser in-situ joining for continuous co-consolidation of carbon fiber-reinforced thermoplastic laminates

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Abstract

Advanced laser in-situ joining (CONTIjoin) is a newly developed process for continuous co-consolidation of multidirectional carbon fiber-reinforced thermoplastic laminates onto a substrate material. In contrast to traditional lay-up techniques, like automated fiber placement (AFP) or automated tape laying (ATL), the CONTIjoin process is capable of continuous in-situ co-consolidation of laminates with up to six plies instead of single-layer unidirectional tapes. In the process, a carbon dioxide (CO_2) laser in combination with highly dynamic beam deflection is used to heat up the joining partners in the mating area, while a pyrometer feeds temperature information into a control circuit to maintain a high set temperature accuracy. Without further autoclave post-processing, over 90 % of the mechanical performance of a static heat press co-consolidation was shown in interlaminar shear strength (ILSS) tests. The results are part of the Clean Sky 2 campaign for joining two thermoplastic half-shells of the full-scale multifunctional fuselage demonstrator (MFFD).

Keywords: continuous in-situ co-consolidation; thermoplastic composite; laser welding; multifunctional fuselage demonstrator; automated tape laying

1. Introduction

Due to the sheer size of parts, joining processes are mandatory during manufacturing of an aircraft fuselage, as their production in one single piece is not possible. For composite fuselages consisting of carbon fiber-reinforced high-performance polymers, mechanical fasteners and adhesive bonding are the commonly used solutions (Breuer, 2016). While induced holes for fasteners leed to critical areas of high stress concentrations (Li et al., 2001), adhesive bonding usually requires complex surface pretreatment and curing, therefore limiting production rates (Messler, 2004). Being the common material for composite aircraft design for the last decades, thermosetting resins are gradually replaced by thermoplastic matrix materials (Meyer et al., 2009) like PEEK (polyetheretherketone). With such thermoplastic carbon fiber-reinforced polymers (TCFRPs) thermal joining processes like welding are possible. Developed at Fraunhofer IWS (Dresden, Germany), advanced laser

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in-situ joining (CONTIjoin) is utilizing this key characteristic of TCFRPs for continuous co-consolidation of carbon fiber-reinforced thermoplastic laminates. In this work, the process principle and the influence of the set temperature parameter to the welding quality of TCFRPs are discussed. This work summarizes the major findings of a recent study performed by the authors in Pohl et al., 2023.

2. Materials & Methods

2.1. Thermoplastic laminates

Laminates made out of carbon fiber reinforced thermoplastic low-melt polyaryletherketone (LM-PAEK) (TC1225, Toray) were used. The laminate sheets with a stacking sequence of +45°/-45°/90°/90°/-45°/+45° were manufactured using AFP and consolidated in a double-belt press. Additionally, both sides were equipped with a 60 µm thick neat resin film (APTIV AE™, Victrex) during consolidation. Out of larger laminate sheets, straps with 70 mm width and 1000 mm length were cut using a guilliotine shear.

2.2. Continuous co-consolidation

The setup used for continuous co-consolidation via CONTIjoin is similar to those of AFP and ATL and consists of two major component assemblies (see Fig. 1). The optical component assembly includes laser and pyrometer optics. As the energy source, a continuous wave carbon dioxide (CO_2) laser (Rofin, Germany) with a maximum output power of 3500 W was used. The emitted laser beam with a wavelength of 10.63 µm was guided into a high-speed laser scanning system (Raylase, Germany) and is deflected into the nip point, where incoming laminate strap and substrate are in contact.

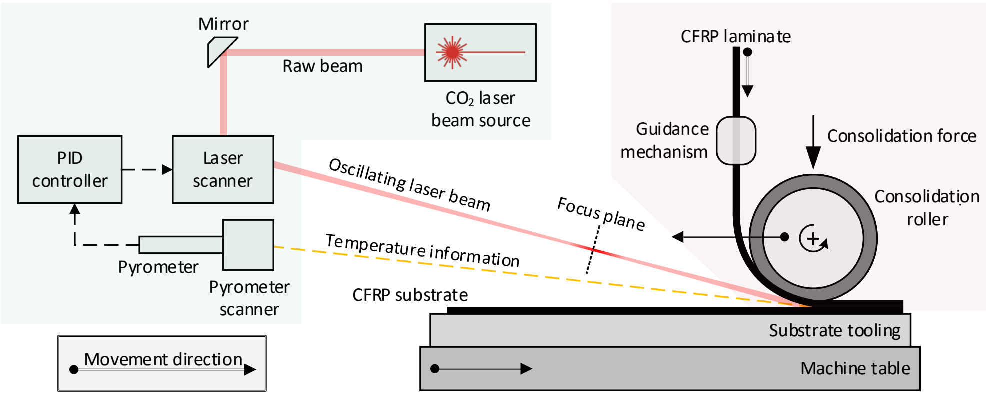

Fig. 1. Schematic illustration of the CONTIjoin setup: (green) optical component assembly and (red) mechanical component assembly (modified from Pohl et al., 2023).

The deflection is carried out in a way, that the laser beam oscillates perpendicular to the feed direction to heat up the whole width of the laminate. Furthermore, a pyrometer (Sensortherm, Germany) is measuring the temperature in the nip point while a separate scanning system (Scanlab, Germany) is used for adjusting its measuring location. The temperature data was fed into a PID control setup to adjust the laser power accordingly to the chosen set temperature. The maximum laser output power was set to 1050 W, corresponding to 30 % of the laser system's maximum power.

The mechanical component assembly inhibits the consolidation tool and a strap guidance system for centering the incoming strap onto the substrate. The consolidation tool consists of 16 individual segments with 20 mm width that were equipped with 8 mm thick silicone rubber sleeves (ContiTech, Germany) with a hardness of 40 Shore A for a more homogeneous pressure distribution. To decrease thermal degradation of the material interacting with the laser beam, three nozzles were used to flood the nip point area with nitrogen gas with a pressure of 4 bar. Mechanical component assembly and the substrate are mounted onto a linear axis which itself is placed on a machine table. Linear axis and machine table were moved simultaneously in opposite directions during the layup to maintain the working distance of 900 mm. To manufacture welded laminates for sample extraction, 24-ply monolithic plates were created out of four 6-ply laminates. First, one laminate was placed on the substrate tooling and clamped down at both ends. While a second 6-ply laminate was fed through the strap guidance and underneath the consolidation tool on top of the substrate laminate with a feed rate of 250 mm/min, both were heated in the nip point and pressed together with a consolidation force of 2800 N. To evaluate the influence of the set temperature on the quality of the resulting welds, the set temperature was varied between 350 °C and 400 °C in uniform steps of 10 K. For each parameter set, a length of 150 mm was welded, with 50 mm of space between different parameter sets. After reaching the end of the 1000 mm long strap, the procedure was repeated two times in a way, that areas with the same set temperature are placed above each other, as shown in Fig. 2a.

2.3. Static co-consolidation

As reference, the same 6-ply laminates were co-consolidated in a heat press (COLLIN Lab & Pilot Solutions, Germany) to manufacture a 24-ply monolithic plate. Four laminate plates were placed in a mould (275 mm x 275 mm) and covered with polyimide UPILEX-25S release film (UBE, Japan). After heating with a rate of 5 K/min from room temperature to 365 °C, that temperature was held for 10 min, before cooling with the same rate of 5K/min. During this cycle, a pressure of 2 bar was applied.

2.4. Mechanical testing

Mechanical performance was evaluated via interlaminar shear strength (ILSS) testing according to DIN EN ISO 14130 (see Fig. 2b). Out of each 150 mm long parameter set area of the 24-ply plates 3 samples with 50 mm length, 25 mm width and 5 mm thickness were extracted via waterjet cutting. Due to the extraction direction, the 90°-layers are parallel to the longitudinal direction of the sample. A loading speed of 1 mm/min was used during testing.

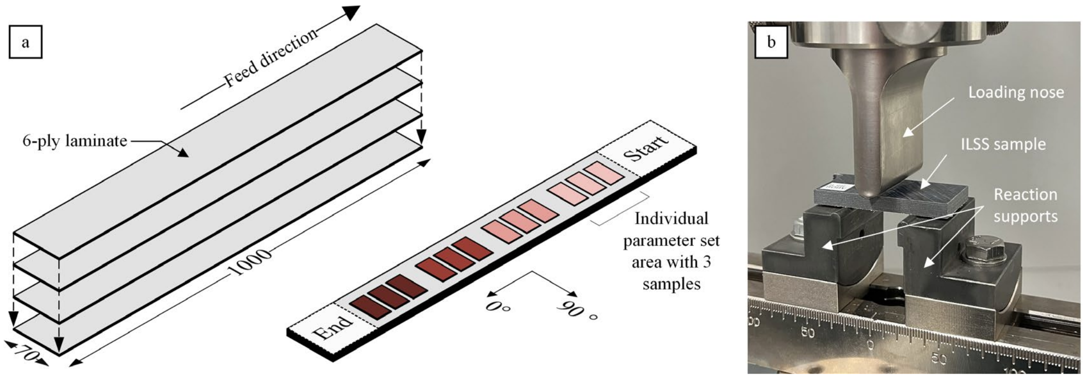

Fig. 2. Illustration of a) welding procedure and sample extraction areas and b) ILSS testing setup (modified from Pohl et al., 2023).

3. Results and discussion

3.1. Pyrometric temperature control

The combination of pyrometric measurements and the laser power output control circuit enabled the set temperature to be held accurately, with standard deviations lower than 2.5 K being observed for a whole heating phase. An exemplary graph displaying measured temperature and laser power output is shown in Fig. 3. After an initial phase of maximum laser power output to heat up the materials to set temperature, the mean power output settles and oscillates around a value of approximately 600 W. When the laser emission is stopped at the end of the welding sequence, atmospheric cooling of the materials takes place up to room temperature.

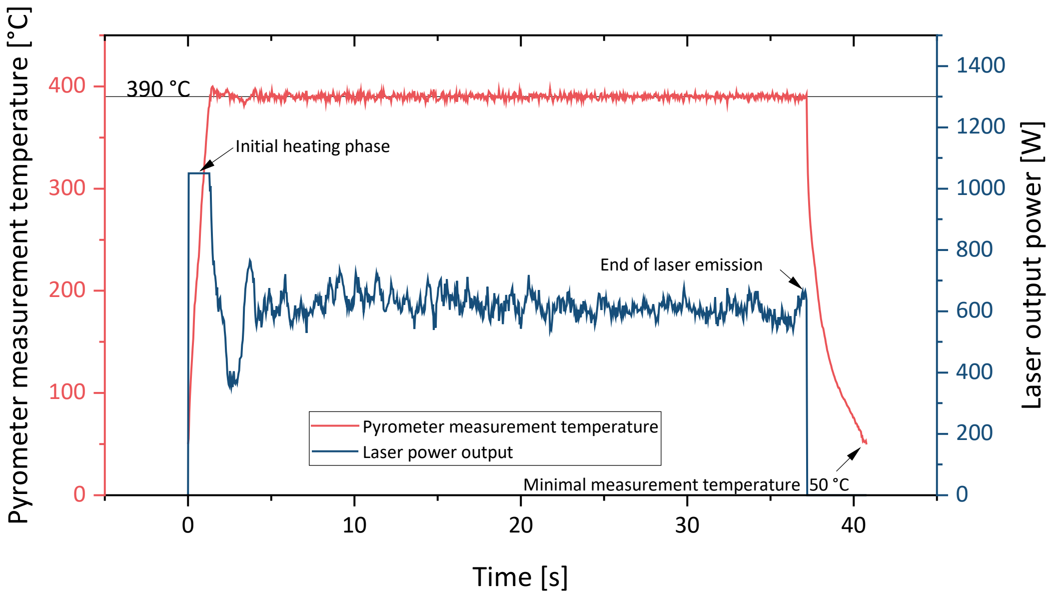

Fig. 3. Graphs of pyrometer measurement temperature and corresponding laser output power of the third welding sequence for the 390 °C set temperature sample.

3.2. Mechanical testing

For all tested samples of each parameter set and the heat press reference, the mean ILSS values are shown in Fig. 4. The standard deviations of the two co-consolidation techniques were comparable in all cases. The statically co-consolidated samples reached the highest strengths of 53.8 MPa. The laser in-situ joined samples showed lower strength, with a maximum strength at 360 °C set temperature of 48.5 MPa, corresponding to approximately 90 % of the reference strength.

An further increase in set temperature above 360 °C lead to a decrease in strength, which could be explained by amplified effects of thermal degradation. At higher set temperatures, higher laser energy levels are required to maintain these temperatures, which have shown to be leading to carbonization effects on the surface of PEEK (Gaitanelis et al., 2023). This could lead to shielding effects at the laminates' interfaces at elevated temperatures.

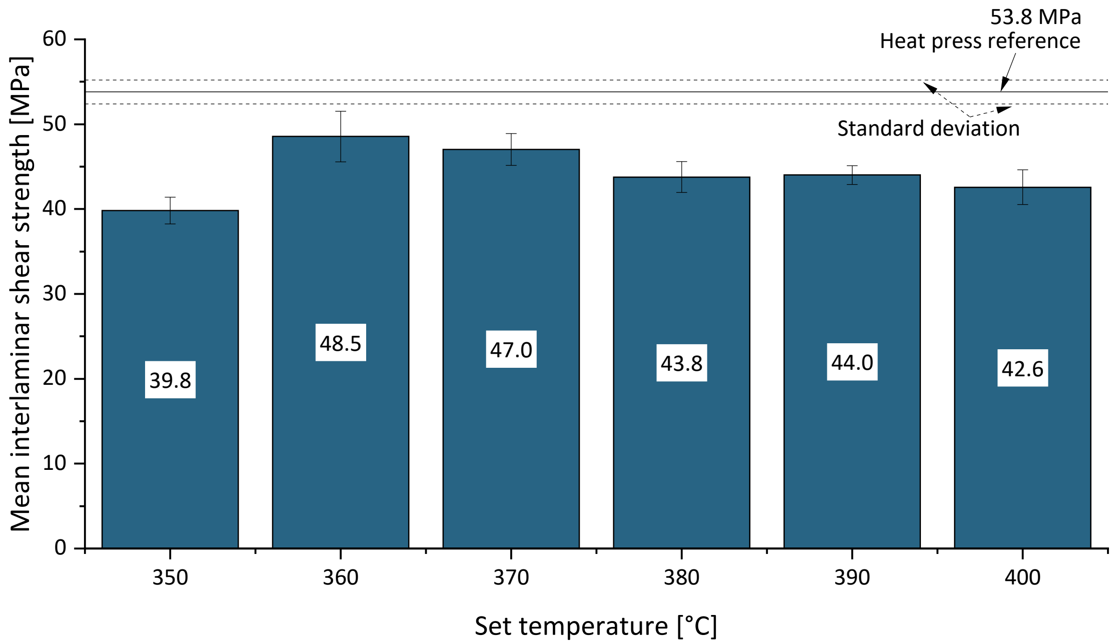

Fig. 4. Illustration of the mechanical performance of samples manufactured via CONTIjoin in comparison with the heat press reference (modified from Pohl et al., 2023).

4. Conclusion

In this work, the principle of the developed advanced laser in-situ joining process was developed and used for continuous co-consolidation of multidirectionally carbon fiber-reinforced high-performance thermoplastic laminates (Pohl et al., 2023). Using a CO_2 laser in combination with high-speed beam deflection, it was possible to join four fully pre-consolidated 6-ply laminates to create a 24-ply monolithic plate. The pyrometer-based set temperature control ensured high accuracy to the chosen set temperature through a PID control circuit, with only a few Kelvins temperature deviation. During mechanical testing, interlaminar shear strengths of up to 48.5 MPa at 360 °C set temperature were observed, corresponding to over 90 % of the strength of a static heat press co-consolidation. At higher set temperature the mechanical performance of the joints decreased, probably due to increasing thermal degradation effects. The results are promising regarding applications for the joining of large-scale thermoplastic composite structures, as intended for the Multifunctional Fuselage Demonstrator in the Clean Sky 2 campaign.

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