

Laser Through Transmission Welding of Non-pigmented Glass-pei to Carbon-pei

Dustin L. Dequine
Kairos Composites Inc.

Anthony Hoult
IPG Photonics Corporation

Brad Harju
Fiberforge Corporation

Stephan Hoetzeldt
Airbus Operations GmbH

ABSTRACT

The performance benefits of fiber reinforced composites are now widely accepted and because of the critical importance of weight reduction throughout the aerospace industry, technical progress in many areas is rapid. In the field of high power lasers for material processing, advances are also being made with the widespread introduction of new technology multi-kilowatt fiber lasers; the work presented here successfully combines both technologies. Laser welding of specific composite combinations is demonstrated and mechanical test results are presented. These results show that good weld strength can be achieved at realistic speeds using standard laser optics. There is a strong possibility of scaling these results up to very much higher speeds and to many different material combinations; this will expand the opportunities for this technique considerably.

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INTRODUCTION TO LTTW FOR COMPOSITES

Many advanced structural applications require the joining of a thin sheet of woven glass-fiber composite to a thicker carbon or glass composite stiffener. Typical applications include stiffened panels for aircraft interiors, aircraft control surfaces, and helicopter rotor blade trailing edges. For most applications, the stiffener may function as a doubler (such as may be necessary to increase local bearing loads), or as a stiffening member (to limit deflection/buckling of the facesheet under load). For thermoset composite applications, the thin facesheets are typically adhesively bonded to the thicker substrates. For thermoplastic composites, the facesheets may either be adhesively bonded (like thermosets), or welded. Potential thermoplastic welding methods include

induction, resistance, vibration, hot plate, and laser through-transmission welding (LTTW) [1]. LTTW is accomplished by transmitting a laser through an upper work piece (transparent or translucent to laser wavelength) onto a lower work piece (absorbent at laser wavelength) and melting the two work pieces together at the interface, as illustrated in [Figure 1](#) [1]. It is the adaptation of this near infra red LTTW technique to the welding of composites for the aerospace industry that is under investigation here.

Lasers have been used for welding polymers for many years [2] and applications for this LTTW technique are now spread across the automotive, medical and consumer product industries and hence a wide range of thermoplastic materials have been employed. In this case, the amorphous thermoplastic polymer, polyetherimide (PEI), is now being specified more widely as a matrix material for aerospace

composites due to its high temperature resistance, but no evidence has been found of these materials previously being welded using the LTTW technique.

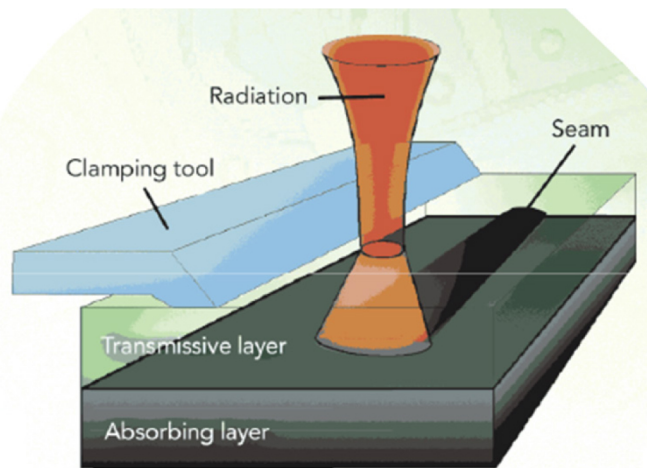


Figure 1. Principle of through-transmission welding

Several different laser types and four different wavelength ranges have typically been used for laser welding polymers and the importance of wavelength cannot be overemphasized. The brief introduction below categorizes the laser types that have been used by wavelength range:

1. Far infra-red carbon dioxide CO₂ lasers emitting at 10.6 μm wavelength.
 - Only used for very thin film or sheet polymer welding
2. Near infra-red (800-1100nm) solid state lasers, fiber lasers and direct diode lasers
 - Widely used for LTTW
3. Short infra-red erbium fiber lasers, $\sim 1.4\text{-}1.50\mu\text{m}$
 - Recent development for colored polymers
4. Short infra-red thulium fiber lasers and holmium lasers, 1.9 - 2.0 μm wavelength
 - Recent developments for welding optically clear polymers [2]

One of the major benefits of the near and short infra-red lasers is that they are now very commonly transmitted to the work piece via flexible fiber optic cables. This dramatically simplifies the requirements of the complete motion system. A lightweight final optic, known as the laser machining head, can be used to manipulate the laser beam accurately and at high speed over the surface to produce the bond. Moving the laser beam rather than the work piece is more cost effective, especially when welding large aerospace components. Full CNC control ensures maximum flexibility of operation and many other significant infrastructure benefits.

The relatively recent introduction of high average power near infra-red fiber lasers (compared to older technology fiber

delivered lasers) as used in this work has made the LTTW process more attractive. These fiber lasers are widely known to be more stable and reliable than older fiber delivered lasers. In the case of fiber lasers, the laser beam is actually generated within the active fiber itself and no free space components are involved in the laser resonator. Increased reliability and stability are widely quoted benefits of this laser type.

Related work has been undertaken using lasers to in-situ consolidate pre-impregnated (pre-preg) reinforcing fibers using high power direct diode infra-red lasers [3]. However, this work focuses on the different technique of using lasers to join existing fiber reinforced components, usually as an alternative to adhesive bonding.

The use of the different fiber and filler combinations brings additional complications for the LTTW technique; as we have seen, this process relies on transmission of a significant amount of thermal energy through the upper layer of the joint through the interface to produce melting, wetting and bonding between the two faying layers. Long fiber reinforcement of both upper and lower layers with many different possible weave patterns and fiber types all affect the transmission and absorption of the laser light and hence complicate the process.

Typically, un-pigmented or natural glass-fiber thermoplastics are laser-welded because of greater transparency to IR wavelengths than pigmented material [4]. However, if the end application requires a pigmented finish, weight and cost may be reduced by using matrix-pigmented glass-fiber thermoplastic composite with a consequent improvement in the cosmetic appearance of the weld.

1. BASICS OF LTTW

It is well known that for laser welding of polymers, only a low power density is required [3]. High power density as is required for metal processing causes almost instantaneous charring, and the carbon thus generated causes a dramatic increase in absorption, leading to rapid thermal runaway and irreversible damage. However, as is common with most welding processes, once an appropriate power density has been identified for a particular material combination, the two primary processing variables are laser power and process speed. Key derivative quantities that control the quality of laser welding, power density and line energy are given below as equations 1 & 2 [6].

$$PD = \frac{P}{a}$$

Equation (1)

PD: power density [W/cm^2]

P: power [W]

A: area of laser spot [cm^2]

$$Es = \frac{P}{v}$$

Equation (2)

Es: line energy [W s/m]

P: power [W]

v: speed [m/s]

It is also important to achieve high enough power density to achieve rapid melting of the polymer matrices to enable high melting and welding rates and to achieve high joint strengths [6]. It is also important to control line energy; too much heat input produces bubbling or other degradation phenomena, too little line energy produces insufficient melting.

2. EXPERIMENTAL PROCEDURE

The initial trials reported here make up the first part of a larger body of work aimed at using the flexibility of modern composite lay-up techniques to:

1. Produce composite components that have the required combination of fibers and fillers to give the mechanical and cosmetic properties required.
2. To understand the effect of fiber and filler properties on the laser transmission welding process.

2.1. Laser Transmissivity

The primary objective for this section of the work was to weld woven glass-reinforced PEI facesheets to uni-directional carbon PEI stiffeners. Preliminary testing was required to assess the transmissivity of possible material combinations to determine the potential of several glass-fiber facesheet and glass-fiber and carbon-fiber stiffener material configurations for laser welding.

Transmission trials were performed on E-glass and S2-glass reinforced sheets over a range of thicknesses and pigmentations. Initial trials were carried out using a 940nm wavelength diode laser source with 3mm spot size, although after a fiber laser was chosen for the welding trials, further transmissivity trials were carried out with this 1070nm fiber laser with a 4.2mm diameter collimated beam output.

2.1.1. Laser transmission results

The results of the transmission tests are shown in Table 1:

All facesheet configurations were evaluated and with the exception of the painted E-glass specimen and the thicker white pigmented specimen, showed good potential for weldability based on % transmission. The transmission is plotted against material thickness in the figure below:

As a general rule, > 20% transmission is preferred for welding to be successful, though it has been shown to be possible at 10%. The transmission results indicate that, using a fiber laser, un-pigmented S2-PEI is weldable up to 1 mm thick but pigmentation will need to be low at this thickness.

Table 1. Laser transmission results

Glass Fiber Type	Thick-ness (mm)	Treat-ment	Laser	% Trans-mission	Weld-ability
E-Glass	0.25	natural	Diode, 940nm	58%	Excellent
E-Glass	0.5	natural	Diode, 940nm	41%	Excellent
E-Glass	0.25	white painted	Diode, 940nm	14%	Not possible
E-Glass	0.85	white pigmen- ted	Diode, 940nm	3%	Not possible
S2-Glass	0.5	Hybrid: 1 ply white pigmen- ted, 1 ply	Fiber, 1070 nm	22% fiber laser	Excellent
E-Glass	0.25	white pigmen- ted	Diode, 940nm	18%	Good
S2-Glass	0.25	Natural	Fiber, 1070 nm	71% fiber laser	Excellent
S2-Glass	0.25	white pigmen- ted	Fiber, 1070 nm	29% Fiber laser	Excellent

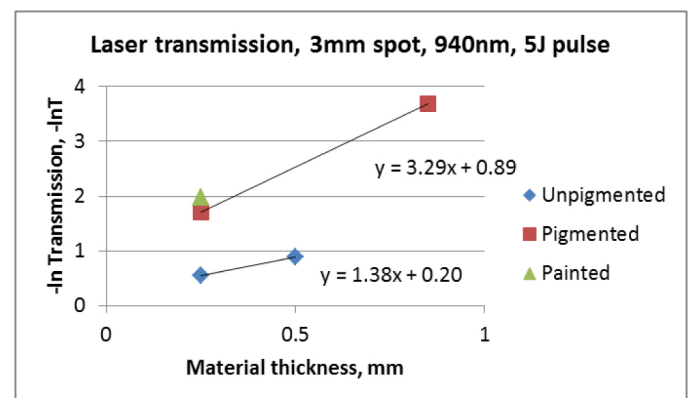


Figure 2. Laser transmission vs. thickness