LASER THROUGH-TRANSMISSION WELDING OF WHITE-PIGMENTED GLASS-PEI TO CARBON-PEI

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1 Introduction to laser through-transmission welding (LTTW) for composites

Many advanced structural applications require the joining of a thin sheet of woven glass-fiber composite to a thicker carbon-fiber or glass-fiber 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 stiffeners. For thermoplastic composites, the facesheets may either be adhesively bonded (like thermosets), or fusion 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 [2]. 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 [3]. 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 studied. 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.

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. Far infra-red (10.6 µm wavelength) carbon dioxide CO2 lasers are used only for very thin film or sheet polymer welding. Near infra-red (800-1100 nm) solid state lasers, fiber lasers and direct diode lasers are widely used for LTTW. Short infra-red erbium fiber lasers (~1.4-1.50 µm) are a recent development for colored polymers. Short infra-red thulium fiber lasers (~1.9 – 2.0 µm) thulium fiber lasers and holmium lasers are a recent development for welding optically clear polymers [3].
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.

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. This paper examines glass-PEI facesheets pigmented with titanium dioxide (Ti02) welded to carbon-PEI stiffeners.

2 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 Equation 1 & 2 [6].

\[
PD = \frac{P}{A} \quad (1)
\]

PD: power density [W/cm²]

\[
P: \text{ power [W]}
\]

\[
A: \text{ area of laser spot [cm²]}
\]

\[
Es = \frac{P}{v} \quad (2)
\]

Es: line energy [W s/m]

\[
P: \text{ power [W]}
\]

\[
v: \text{ speed [m/s]}
\]

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.

3 Experimental procedure
This is the second paper published as a 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.

The first paper in the series reported transmissivity of many different variants and thicknesses of glass-PEI facesheets, thicknesses, as well as weld parameters and strength for un-pigmented (natural) glass welded to carbon-PEI stiffeners [7]. This paper reports weld strength, weld parameters, and micrographs of white-pigmented glass-PEI facesheets welded to carbon-PEI stiffeners.

4 LTTW trials
Having selected the most promising candidate materials from the transmissivity trials, initial welding trials were performed using the near infra-red Ytterbium fiber laser shown in Figure 2. The particular model used produces a maximum average power of 250 watts average power, but for these initial trials a lower average power was required. The beam from the fiber laser is delivered via the 200 µm core diameter fiber to the laser output housing which is mounted on a moving head gantry, which is moved in X and Y axes over the stationary work piece.

4.1 Weld tooling
The clamping system used to establish the parameters and weld the test specimens is a non-contact method consisting of a transparent cover of borosilicate glass compressing the facesheet via multiple toggle clamps. The setup is illustrated in Figure 3.

4.2 Spatial output of the fiber laser
Although a wide range of laser beam spatial profiles can be produced from a single laser by choosing different fiber diameters and collimator focal lengths, a multi-mode laser was chosen for this work. The objective here was to produce a ‘flat-top’ beam to minimize overheating in the central part of the weld line. The particular fiber laser model chosen therefore has a standard 0.05 mm core diameter fiber and a 0.2 mm ‘feed fiber’ that feeds the beam into the beam delivery optics. In this case, a 65 mm focal length collimator was used to change the diverging beam from the fiber into a parallel beam. This optical configuration produces a 4.2 mm diameter collimated (parallel) beam in the near infra-red range. An in-process weld with a tracing beam is depicted in Figure 4.

4.3 Material configurations
The final materials evaluated for welding parameters and joint strength are identified in Table 1.

4.4 Ranging trials: White-pigmented glass-PEI facesheets (S2_WP_0.25)
Trials were performed to weld pigmented facesheets (S2_WP_0.25) to carbon (AS4_0°) stiffeners. Trials and parameters for welding S2_NAT_0.25 to AS4_0° are fully detailed in Reference 8 and not repeated here.

For the initial qualitative assessment, five parameter configurations were evaluated:

- A1. 40W; 10mm/s
- B1. 60W; 10mm/s
- 2. 60W; 9mm/s
- 3. 60W; 8mm/s
- 4. 60W; 7mm/s
- 5. 60W; 6mm/s
The welds were peeled back manually for the quantitative assessment. In the figure below, the carbon stiffener (AS4_0\(^{\circ}\)) is at left, and the pigmented facesheet (S2_WP_0.25) at right. The test numbers are indicated next to the respective weld trials.

As evident in the visuals, the weld failure mechanism changes from pulling matrix from the S2_WP_0.25 facesheet at high speed (Weld 1) to pulling fibers off the AS4_0 stiffener at low speed as the heat penetrates further into the material (Weld 5). The specimen was sectioned across all 5 welds in a pristinely welded area. 6x micrographs were taken and stitched together in order to look for voids on a laminate level. A micrograph of the S2_WP_0.25 facesheet welded to the AS4_0 at 4 mm/s is illustrated in Figure 6.

For these weld parameters, small voids ~0.02-0.04 mm are apparent near the center of the weld, however the majority of the weld line appears to be free of voids. 20x micrographs were taken in order to observe the intermixing of the PEI in the AS4_0 with the PEI in the S2_WP_0.25. Figure 7 shows, for each of the five weld locations, the interface at an area of the facesheet weave which is resin dominated, and near the center of the weld.

The PEI in the AS4 stiffener appears slightly greyer than the white-pigmented PEI in the facesheet. In Weld 5, slightly more mixing of the matrices and fibers between the two laminates can be seen than for Weld 1. Weld 5, however, has a large void at the interface. This void is likely due to under-heating along the center relative to the edges, and corresponds to the white strip in middle of Weld 5 in Figure 5.

The welds were also analyzed for the five weld locations at areas were the weave is fiber dominated, shown in Figure 8.

There does not appear to be a notable difference in the fiber-dominated interface regions of the weld, possibly indicating that the weld strength in these regions is not as sensitive to different weld parameters.

Observations from the screening study are:

- Destructive micrographs show location of significant void near the center of Weld 5.
- Visual inspection of peeled laminates show white strip in center of Weld 5 – possible area of local deconsolidation or poor adhesion.
- Qualitative peel strength is higher for Welds 4 & 5 than 1-3.
- The voids that were observed in the overall laminate appear to be limited to very a very small region at the center of the weld and at the weld interface.
- The voids do not appear to extend into the facesheet or stiffener laminates.

Because the Weld 4 micrographs showed no significant voids, had a qualitatively strong peel, and resulted in both facesheet and carbon fiber failure, the mechanical strength panels used parameters which produced visual results similar to Weld 4.

4.5 Ranging trials: Hybrid pigmented/un-pigmented (S2_HYB_0.5) facesheets

Additional ranging trials were performed using the thicker 0.5 mm thick hybrid facesheet (S2_HYB_0.5) welded to the AS4/PEI (AS4_0) stiffener. Both sides of the hybrid facesheet are shown in Figure 9.

To accomplish the weld, detailed adjustments to the control of the laser and welding process allowed increased average power to be used whilst avoiding the degradation and charring seen in earlier attempts. It was therefore possible to increase laser power as high as 134 watts in the collimated beam, corresponding to 122 watts at the work piece (after passing through the glass clamping plate). At powers higher than this, relating to a power density > 870 W/cm\(^2\), rapid localized charring was seen if any
contamination was present. It was noted that this was particularly true in the case of the un-pigmented facesheets. The authors’ feel that this power density is the absolute practical limit for a production welding process as complete cleanliness will be very difficult to obtain in a manufacturing environment.

5 Weld parameters for strength testing
Developing appropriate tooling and understanding the line energy limits to the process enabled mechanical testing samples to be prepared at higher average power and higher weld speeds than in Section 4.4. The highest power of all was used for the 0.5 mm hybrid facesheet material. The welds for all tests of the 0.25 mm facesheets were performed at 70W and 13mm/s using the same 4.2 mm collimated beam. Table 2 summarizes the weld configurations and parameters used for preparing the samples for strength testing.

6 Strength testing
Lap shear and flatwise tension (FWT) tests were performed on S2_WP_0.25 and S2_HYB_0.5 facesheets welded to 1.0 mm AS4_0 stiffeners. Additional tests on un-pigmented facesheets (S2_NAT_0.25) welded to AS4_0 stiffeners are also included here for comparison [7]. The tests represent between 3 and 8 replicates of each test type.

Fabrication of the flatwise tension specimens was accomplished by first welding 100 mm x 150 mm facesheets to stiffeners of the same size. The welds were performed in two sets of three passes, each pass 4-5 mm wide. The welded specimens are depicted in Figure 10.

The welds on the white pigmented facesheet are barely visible to the naked eye. C-scans of the welded panels were performed with an Olympus phased-array OmniScan, shown in Figure 11.

In the NDI scan, the blue represents areas of good transmission, while the red is poor transmission. Because of the extremely thin facesheet, the NDI resolution is limited, however overall the scan reveals intimate contact (good welds) with some notable variation from pass to pass.

Next, specimens were sectioned from the welded plaques to final dimensions of 40 mm x 40 mm in order to eliminate edge effects, as depicted in Figure 12.

The area of the weld on each specimen between facesheet and stiffener measured 40 mm x 13 mm. Each specimen was bonded between 40 mm steel blocks using Hysol 9359.3 and tested according to a modified ASTM C297 method.

The lap shear specimens were fabricated and tested according to ASTM 3165 (single shear) by welding 100 mm x 150 mm facesheet and stiffener plaques together with an overlap of 5 mm. The lap shear length of 5 mm was selected based on the width of a single collimated beam w/o optics, and because this represents the smallest width expected in the aircraft application. Hence, the narrow welded lap shear test strengths incorporate necessary peaking factors for use in preliminary design values. To ensure the peel moment at the weld line was minimized, material matching the required thickness and modulus was bonded to the facesheet and stiffener, according to ASTM 3165. The test results are shown in Figure 13.

The vertical bars represent one standard deviation. Load vs. displacement curves for representative lap shear specimens of each material configuration are shown in Figure 14, and the flatwise tension curves are shown in Figure 15.

The flatwise tension plots are fairly linear to failure and similar in slope. The lap shear plots, in contrast, differ significantly between facesheet category. The un-pigmented glass loads up rapidly and gradually goes non-linear before failure. The pigmented and
hybrid facesheets, on the other hand, experience an extended linear period after an initial highly non-linear region. Recalling that it is the un-pigmented side of the hybrid facesheet that is welded to the AS4 stiffener—not the pigmented side—may be an indication that the strength difference is in the AS4 stiffener, not in the facesheet. A future design of experiments will examine in more detail the failure mechanism for each configuration and whether the non-linearity is due to test effects or progressive failure in the specimen.

A lap shear failure specimen is shown in Figure 16 and a flatwise failure specimen is shown in Figure 17.

In the FWT test, both the stiffener and facesheet failed, indicating a good mixing of the matrices at the faying surfaces. In the lap shear test, there was white-pigment resin observed on the AS4-PEI, however no carbon fibers are observed on the glass.

7 Summary and conclusions

7.1 Strength viability of laser through-transmission welding

This report has demonstrated the feasibility of fusion-joining pigmented glass-PEI facesheets to carbon-PEI stiffeners using state-of-the-art fiber laser technology. The report documents the significant lap shear and flatwise tension strengths achieved for pigmented 0.25 mm S2-PEI facesheets to AS4-PEI and stiffeners. It has also documented the viability of welding hybrid pigmented/un-pigmented 0.5mm S2-PEI facesheets to AS4-PEI stiffeners.

Although not quantified accurately in these trials it appears that, unlike other welding techniques, relatively low clamping pressure is required to keep the faying surfaces for these material configurations in contact for wetting and ‘reptation’ to occur. Reptation is described as the intermingling of long polymer macromolecules that is necessary to achieve successful bonding [5]. Further, as the micrographs in Figure 6-8 indicate, welds with little porosity are possible at very low clamping pressure.

A major benefit from this fiber laser approach is that the high brightness (focusability) of the fiber laser enables a collimated or parallel beam to be used to achieve this approximately optimized power density used in these trials.

Average laser powers of up to several kilowatts are currently available commercially, and scaling these results up to larger spot sizes, larger bonded areas and hence faster weld coverage rates is a relatively straightforward optical exercise.

8 Further work

Near term planned work is to expand the range of applications of this technique to include welding pigmented glass-PEI facesheets to glass-PEI stiffeners. Additionally, the optimum power density, line energy, power and speed will be established for each combination.

Weld speeds can be enhanced using higher average power lasers and relatively simple optics to modify the laser beam.

9 References

10 Tables

Table 1. Materials for Evaluation

<table>
<thead>
<tr>
<th>Configuration</th>
<th>ID</th>
<th>Description</th>
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</thead>
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<tr>
<td>Facesheet Materials</td>
<td>S2_NAT_0.25</td>
<td>S2-Glass weave (style 7781), PEI matrix, natural (no pigment), 0.25 mm thick, 0/90 fiber orientation</td>
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<tr>
<td></td>
<td>S2_WP_0.25</td>
<td>S2-Glass weave (style 7781), PEI matrix, white pigmented with TiO2, 0.25 mm thick, 0/90 fiber orientation</td>
</tr>
<tr>
<td></td>
<td>S2_HYB_0.5</td>
<td>Hybrid laminate: 1-ply S2_NAT_0.25 and 1-ply S2_WP_0.25</td>
</tr>
<tr>
<td>Stiffener materials</td>
<td>AS4_0°</td>
<td>AS4 (intermediate modulus carbon-fiber), PEI matrix, 60% fiber volume, uni-directional laminate of layup [0/90]2s, 1.0 mm thick, 0° fiber orientation at faying surface (relative to load direction)</td>
</tr>
<tr>
<td></td>
<td>AS4_90°</td>
<td>Same as above, but with 90° fiber orientation at faying surface</td>
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Table 2. Weld configurations and parameters

<table>
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<tr>
<th>Face-sheet</th>
<th>Stiffener</th>
<th>Wave-length (nm)</th>
<th>Weld Power (W)</th>
<th>Weld Speed (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2_NAT_0.25</td>
<td>AS4_0°</td>
<td>1070</td>
<td>70</td>
<td>13</td>
</tr>
<tr>
<td>S2_WP_0.25</td>
<td>AS4_0°</td>
<td>1070</td>
<td>70</td>
<td>4</td>
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<tr>
<td>S2_HYB_0.5</td>
<td>AS4_0°</td>
<td>1070</td>
<td>134</td>
<td>6</td>
</tr>
</tbody>
</table>
11 Figures

Figure 1. Principle of through-transmission welding

Figure 2. Output housing on Cartesian motion system

Figure 3. Laser welding fixture

Figure 4. In-process weld of pigmented facesheet
Figure 5. Pigmented glass facesheet welded to carbon stiffener.

Figure 6. 6x laminate macro, S2_0.25_WP welded to AS4_0°

Welded area

Edge of weld

Edge of weld

facesheet (S2/PEI, 0.25mm, WP)

Stiffener (AS4/PEI, 1.0mm,)

Minor voids in weld line
Figure 7. Weld interface comparison for different weld parameters, resin rich area.

Weld 1

Weld 2

Weld 3

Weld 4

Weld 5

20X Micros of resin-dominated area

S2/PEI Weave

Weld Interface

AS4/PEI UD Tape

Significant void well within weld.
Figure 8. Weld interface comparison for different weld parameters, fiber dominant area

Figure 9. Hybrid facesheet (S2_HYB_0.5) prior to welding, backside (top) and front side (bottom)

Figure 10. Flatwise tension welded plaques, pigmented facesheet side (top) and stiffener side (bottom)
Figure 11. NDI Scan of welded panel

Figure 12. Welded panels sectioned for flatwise tension testing

Figure 13. Strength of pigmented and un-pigmented facesheets welded to AS4/PEI
Figure 14. FWT: Load vs. displacement for representative specimen

Figure 15: Failed lap shear stiffener (L) and facesheet (R)

Figure 16. Failed flatwise tension stiffener (L) and facesheet (R)