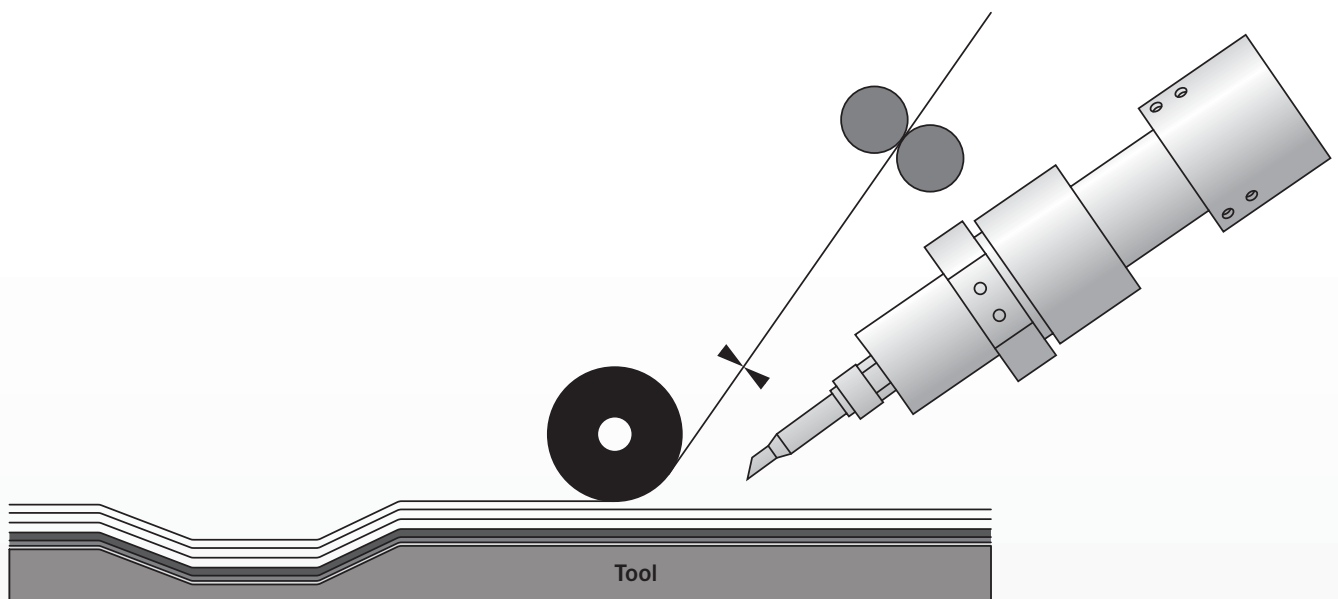


Development of Laser Heating

FOR PROCESSING THERMOPLASTIC COMPOSITES



Abstract

Development of Laser Heating to be used in the Processing of Thermoplastic Composites

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In recent history, the demand for thermoplastic matrix composites has increased significantly and new applications are constantly being explored.

This increase in demand has led to increased pressure to process material faster and more efficiently to allow it to be more cost competitive with the other options. The Trelleborg Sealing Solutions robotic, in-situ fabrication method for thermoplastic composites creates parts that are high quality, consistent and repeatable. Additionally, the process does not require any post cure, eliminating the autoclave step and corresponding costs common to other composites. However, current heating methods are near the upper limit of output, so to see significant increases in processing rates, new heating technologies need to be implemented.

Trelleborg Sealing Solutions explored several different types of heating technologies to determine which options had the greatest potential for replacing current in-situ processing heating systems.

Improved HGT (Hot Gas Torch) systems, ultrasonic heating systems and laser heating systems carbon dioxide, diode and fiber were considered.

After the comparisons were completed, the fiber laser system was chosen to be used in the development trials. To complete the processing trials, a representative workcell was designed and built to utilize the laser, custom optics were developed to optimize the laser output and test rings were made and tested.

These experimental results were compared to the results achieved with existing processing technology. Preliminary test results show that laser processing can create bond strengths comparable to current processing methods at significantly faster speeds.

This paper will outline the heating systems that were examined, explain the usage of the custom optics and summarize the test results.



1. INTRODUCTION

The use of thermoplastic composites is becoming more and more accepted in industry. Because of this, the methods used to process these composites need to advance. Current processing methods tend to be labor intensive (hand-lay-up, autoclaving) or inefficient (Hot Gas Torch). Current technologies also tend to be slow and expensive when compared to the methods used to fabricate thermoset composite structures.

In general, thermoplastics offer several advantages over thermosets (toughness, corrosion resistance, etc.), but in order for them to continue to gain in popularity, they need to be able to be processed quickly, efficiently and cost effectively.

The first step in improving the cost and efficiency of processing thermoplastic composites is to minimize the amount of labor required. This can be accomplished by using robots to perform in-situ processing of the parts. In-situ means that the parts are fully consolidated during the lay-up process and do not require a post cure or other post-fabrication consolidation step. By using robots to make fully consolidated parts, the amount of human labor is greatly reduced and the part consistency, repeatability and quality are improved.

The use of robots in composite part fabrication has been around for several decades and is generally well accepted. The next challenge involved in getting thermoplastic composites to be more viable in various markets is to reduce the overall cost and fabrication time. The current technologies used to heat the composite during in-situ fabrication are at their upper limits in terms of the amount of energy they can impart, which limits the processing speeds.

In order to process faster and therefore less expensively, methods capable of increased energy generation and transfer need to be developed.

This paper will give a brief summary of the different types of in-situ processing methods being used and investigated and their general effectiveness. After that, it will focus on Trelleborg Sealing Solutions development of laser processing, from the selection of the laser to use, to the customization of the optics, to the process trials and results.



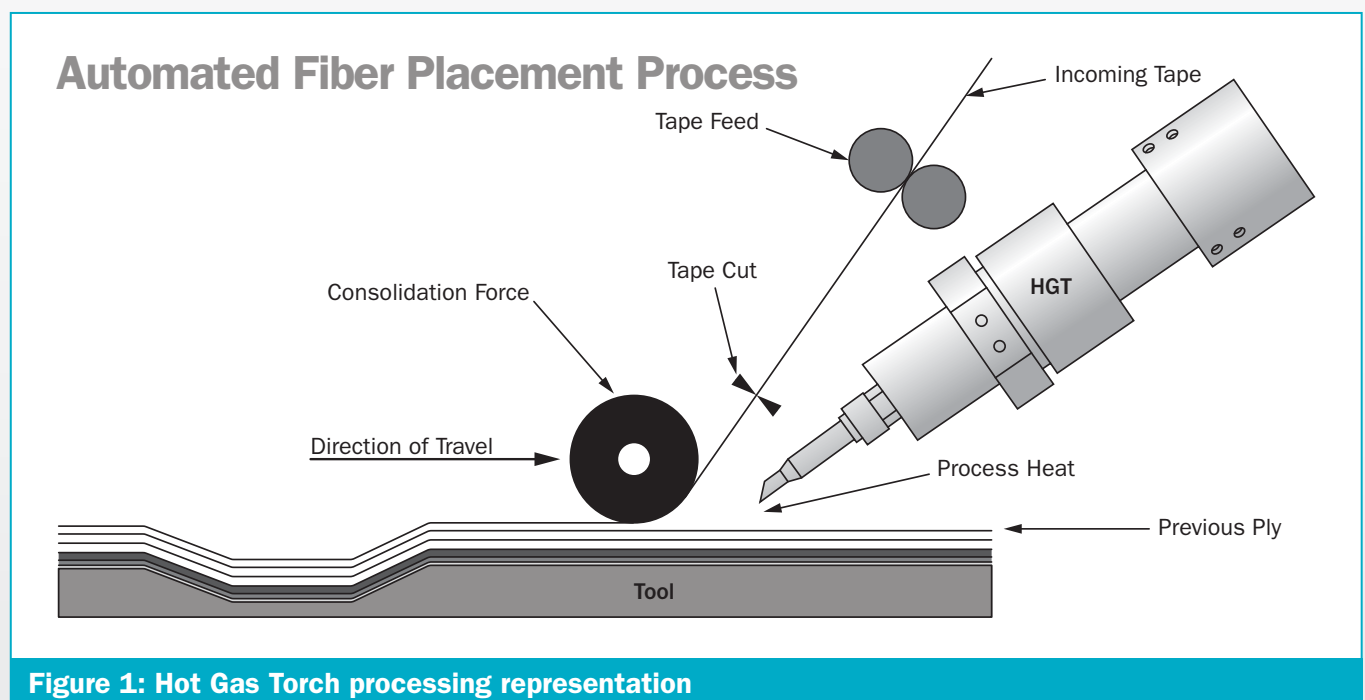
2. TYPES OF HEATING METHODS FOR IN-SITU PROCESSES

2.1.1 Hot Gas Torch

Currently, the most popular method used to melt incoming thermoplastic composite tape and corresponding substrate is the Hot Gas Torch, or HGT. A Hot Gas Torch, in the simplest terms, is a cartridge heater that uses electrical current run through resistors to create heat. An inert gas, typically nitrogen, is forced into the hot gas torch, heated by the resistors and expelled toward the nip point (the point where the incoming material meets the substrate). The heat of the expelled gas is enough to melt the incoming material and the top layer of the substrate. While both are still molten, they are pressed together with a roller or shoe to create the desired bond.

This method has several advantages. Hot Gas Torches are small, light and very flexible, making them easy to mount on robotic equipment. They can be used for any type of composite and on any geometry. Finally, the technology is proven, relatively inexpensive and easy to set-up and maintain.

However, there are several issues with hot gas torches that are adding to the push for new technologies. First and foremost among the issues is that systems that utilize the hot gas torches are slow when compared to industry desires.



Hot gas torches use convection heating and affect a relatively large area. While this allows them to melt any material and work on any geometry, it is very inefficient with only about 5% of the energy generated going into the composite. Additionally, they are at their upper limit in terms of temperature capabilities, i.e. with the current designs and available materials for construction, they cannot get any hotter.

With the inherent inefficiencies and the inability to create higher temperatures, systems that use hot gas torches have reached their maximum processing speeds. While the relatively slow processing speed is the largest issue, hot gas torches are also difficult to accurately control and they heat a large area which creates a very aggressive environment for all of the other hardware involved.

2.1.2 Ultrasonic Heating and Consolidation

A method looked at as a possible replacement for the hot gas torch is ultrasonics. Ultrasonics use high frequency vibrations to bond incoming composite to the substrate. Incoming composite tape is pressed against the substrate with a shoe or horn. While under pressure, the tape and substrate are subjected to a high frequency oscillation which transmits vibrations through the material. These vibrations create heat through a combination of surface and intermolecular friction. When the friction creates enough heat to melt the composite matrix, the bond is created. This process is very fast and clean as there is generally no flash created.

However, given the surface contact requirements, it is currently limited to essentially flat geometries. It also runs the risk of fiber disruption and damage at interfaces due to the high energy oscillation. Finally, it does not work well with all materials. Materials with high thermal conductivity (e.g. continuous graphite fiber composite) tend to conduct the heat away quickly, making a good bond harder to achieve.

Thermoplastics with high melt temperatures, such as PEEK (polyetheretherketone), also require additional time to achieve a good bond. In both of these instances, the process either has to be slowed to allow enough time for the friction to melt the material on its own, or an additional heating source, such as a heated roller, has to be added to melt the material more efficiently.

2.1.3 Laser Heating and Consolidation

The processing method being researched with the most upsides is laser heating. Lasers use focused light to melt the incoming tape and corresponding area of the substrate. While the tape and substrate are molten, a compaction apparatus (roller, shoe, etc) presses them together to achieve the bond.

There are three types of lasers that have been used in the majority of experimental processing of thermoplastic composites. They are CO², diode and fiber lasers.



CO² Lasers: The earlier attempts at laser processing of composites used CO² lasers. CO² lasers are large, relatively fragile, multi-component devices. CO² lasers create their laser energy by discharging an electrical current or flashing a high power lamp into a chamber containing carbon dioxide along with other gases. The interactions of the gas molecules amplify the input. Mirrors are used to reflect the light and organize it into a coherent beam before it is directed to the desired location.

Most thermoplastic polymers are opaque to the wavelength of the light generated by the CO² lasers (approximately 10.6 microns). In other words, the polymer directly absorbs the energy of the laser and is heated to melt. Larger areas are processed using banks of lasers in series. Like many lasers used to process composites, CO² lasers are fast and efficient compared to IR (infrared) or HGT heating.

However, effectively using a CO² laser is very complicated and tends to require a complex control system. There are several reasons for this. CO² lasers are often pulsed to achieve higher energy levels and their response time is slow when compared to other lasers. As previously mentioned, CO² lasers heat the polymer directly. If the polymer is overheated, which is very easily done with laser heat, it will decompose. The size, relative fragility and complexity of controlling the CO² laser, combined with the potential damage caused by overheating the polymers, makes it less than ideal for this application.

Diode Lasers: As the name implies, diode lasers use diodes to create their light. Most commonly, there is no amplification of the light once it is emitted from the diode. Unlike CO² lasers, most thermoplastic polymers tend to be transparent to the wavelength of light created by diode lasers of sufficient power for engineering grade thermoplastic processing (approximately 0.8 microns).

This means that the laser light passes through the polymer and is absorbed by the composite's fibers. The fibers heat up, and in turn, melt the plastic. By melting the thermoplastic indirectly, diode lasers are much less likely to burn and degrade the polymer. Diode lasers are solid state devices and therefore have no moving parts.

They are small so they can be directly mounted to a robotic processing head and are relatively easy to control. They provide continuous power levels and very fast response times. Diode lasers tend to be relatively inexpensive, but often have insufficient power output for in-situ processing thermoplastics. While it is possible to get diode lasers with power outputs capable of processing the higher temperature thermoplastics at the desired speeds, the price for these units tends to be significantly higher.



Fiber Lasers: Fiber lasers also use diodes as the source for their laser light. Because of this, they have many of the same benefits present with diode lasers. The laser wavelength that they create (approximately 1.0 micron) will pass through most thermoplastic resins. So the lasers melt the polymer indirectly by heating the fibers and are therefore less likely to damage it. They are solid state devices (no moving parts) and their beams are easily and efficiently directed to the robot end effector via fiber optics. They have fast response times and can provide continuous wave output.

The difference between diode lasers and fiber lasers is that fiber lasers direct their diode laser light along doped fiber optics. These fiber optics reflect and amplify the diode laser to pump energy to the desired power levels within the fiber itself. This amplification allows the fiber lasers to operate at the higher power levels required to process high melt point thermoplastics (e.g. PEEK) at high speeds, without the dramatic increase in cost. In other words, fiber lasers provide most or all of the benefits of diode lasers for less cost.

After evaluating the different type of lasers available, Trelleborg Sealing Solutions decided to use a fiber laser, specifically a 2kW Nd: YAG (Neodymium-doped Yttrium Aluminum Garnet) laser from IPG Photonics to perform its research.

2.1.4 Laser Optics

After the laser was selected, attention was turned to the laser optics. With standard optics, the laser beam image is circular and has a Gaussian distribution, i.e. the energy distribution is greatest in the center and falls off towards the edges. Because of the shape and energy distribution of the beam, the center of the composite tape would see more time within the beam and a greater energy level.

This results in inconsistent heating and consolidation across the width of the tape. To remedy this, a custom optic was created. The optic generates a rectangular beam meaning that all points along the width of the tape spend the same amount of time in the beam.

Additionally, the optic redistributes the Gaussian beam to create a flat top profile with even power distribution across the width of the beam. These two attributes result in an optic that provides consistent heating and consolidation across the tape width.



3. EXPERIMENTATION

3.1 First Iteration

For the first iteration of processing trials, Trelleborg Sealing Solutions created a simple winding mechanism that could be used to make test rings. These rings would then be broken to determine the bond strength of the composite. The winding mechanism consisted of a mandrel that the rings are wound around and a compaction roller that provides the pressure needed to press the molten tape and substrate together.

The incoming tape is attached to the mandrel which is used to pull the material through the processing area. The rotational speed of the mandrel is adjusted to control the speed at which the material was processed. IPG provided the use of their Applications Lab and a Nd: YAG laser with focusing optics to perform these initial trials. The focusing optics generated a circular, Gaussian beam. The laser was mounted on an articulated arm robot used to aim the lasers focal point at the nip region; the contact point of the compaction roller and mandrel.

A FLIR infrared camera was used to measure the temperature of the process. The FLIR was not used to control the process, merely monitor it. The position of the robotic arm was not adjusted during the fabrication of the test rings. This setup was used to make a series of test rings at varying process speeds and laser output levels.

These rings were cut into test coupons and broken using a three point bend method. The amount of force required to break the samples was measured and used to calculate the ILSS (Interlaminar Shear Strength) of the sample. A summary of the results is in Table 1 in the Experimental Results Summary at the end of this section.

The results achieved were comparable to results seen with the Trelleborg Sealing Solutions Hot Gas Torch process, but at speeds 50% to 500% faster. Although the results were promising, several potential areas of improvement were identified. The first improvement would be the incorporation of the previously mentioned custom optic. This would provide more consistent, even heating of the incoming tape. The other main item identified for improvement was active control of the location of the focal point of the laser.

In this trial, the location of the laser focal point was fixed. As the wall thickness of the ring increased, the nip region moved up. Since the focal point of the laser was not moved to compensate, more of the laser energy was aimed at the substrate and less at the incoming tape. Additional improvement opportunities were identified but they were lower priority. These improvements consisted of active mandrel and compaction roller temperature control.

3.2 Second Iteration

The second test iteration involved the same set-up as the first iteration, but used the custom optic previously discussed. Sets of process conditions from the first iteration were selected and repeated with the new optic. The results were then compared to validate that the new optic was functioning properly. The test results, summarized in Table 1 in the Experimental Results Section, showed that the custom optic yielded average results slightly better than the standard optic.



Figure 2 - Laser Processing on the Lab Machine

3.3 Third Iteration

The third iteration of testing involved the fabrication of a more sophisticated, lab scale robot that would be used to fabricate the test rings. The robot was designed so that the laser and the infrared camera could be mounted directly onto the processing head. The major advantage of this setup is that the focal point of the laser is adjusted to maintain aim at the nip region as the wall thickness of the test ring increases. This provides consistent energy in the substrate and the incoming tape during the entire fabrication process.

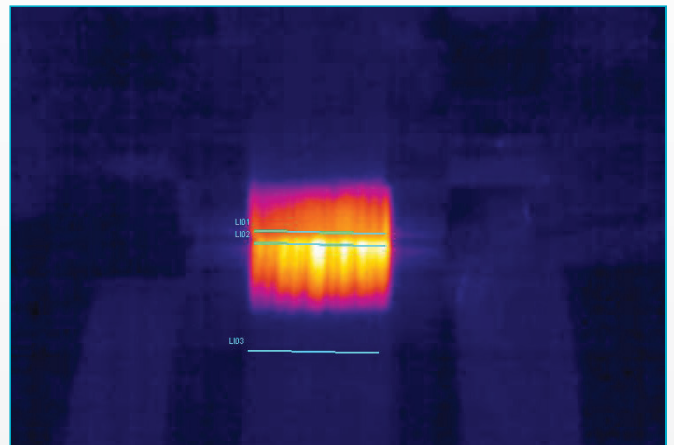


Figure 3 - Infrared Image of Laser Processing

Testing for this iteration is ongoing, but preliminary results show results that are more consistent and equal to the best results seen in previous trials. (See Table 1 in the Experimental Results Section.)

4. RESULTS

4.1 Experimental Results Summary of Processing Iterations

The results for the three experimental iterations are summarized in Table 1 below. Results 1-25 were obtained in the first iteration. Results 26-29 were obtained in the second iteration and results 30-32 were obtained in the third iteration.

Going forward, there are additional areas targeted for improvement. Control of the process can be refined to incorporate the infrared camera in a closed loop system. In the near future the output of the laser will be actively modulated to maintain the optimum temperature at the nip, as measured by the infrared camera. Additionally, plans are underway to modify the thermoplastic composite tape itself.

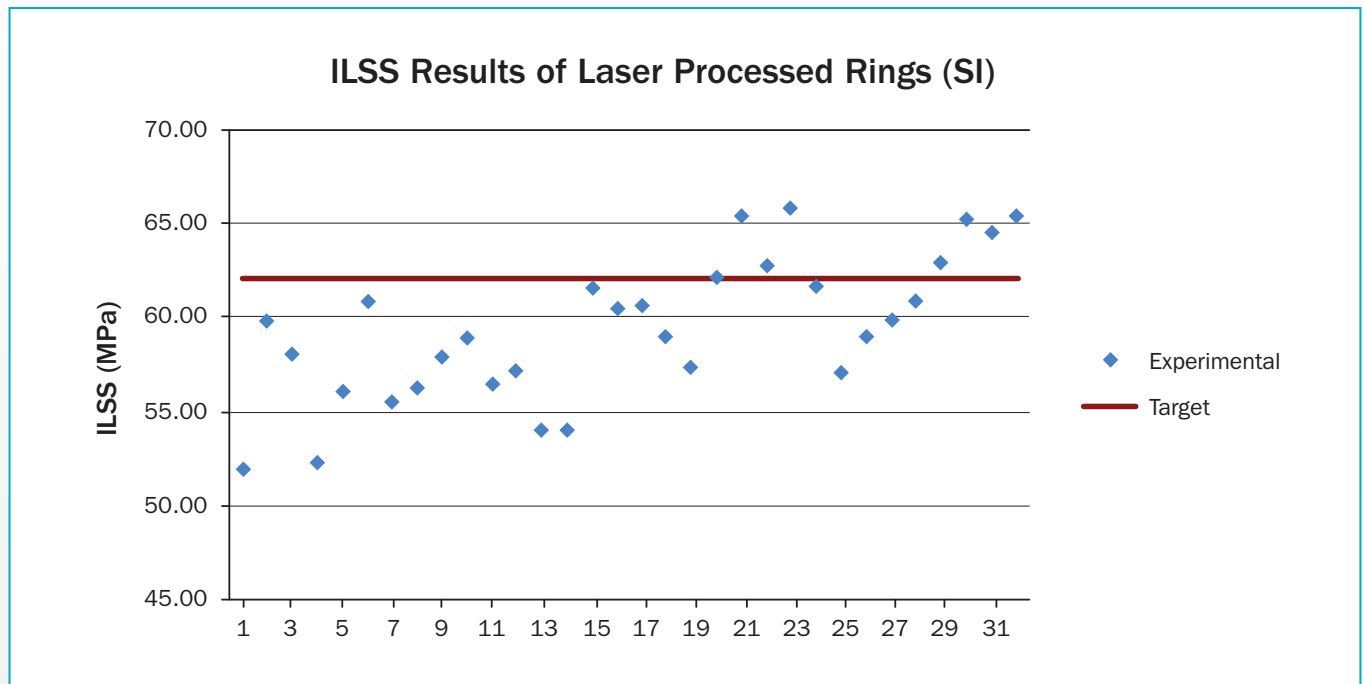


Table 1 - Summarized Experimental ILSS Results

4.2 Future Work:

Over the course of this development Trelleborg Sealing Solutions has chosen the best laser for the process and created custom optics for that laser to optimize energy transfer. Additionally, a lab scale robot has been designed and built to give greater control to the process.

Surface coatings are being developed at Trelleborg Sealing Solutions that will improve the energy absorption of the composite material and correspondingly, the interlaminar bond.

SUMMARY

Laser processing of thermoplastic composites has a very promising future. Development of the process is at continues and it is yielding bonding results that are equivalent to what is achieved with a hot gas torch, but at significantly faster speeds.

Future improvements should see processing speeds and corresponding bond strengths continue to improve.



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