# IN-SITU CONSOLIDATION OF THERMOPLASTIC COMPOSITES USING AUTOMATED FIBER PLACEMENT

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## Abstract

Much effort has been expended by many industries to develop thermoplastic composite structures, the goal of this work being a fully automated manufacturing process. In-situ consolidation (ISC) with automated fiber placement (AFP) of thermoplastic composites (TPC) is a fully automated solution and a true additive manufacturing process. Recent developments in prepreg tapes, laser heating, equipment, and process control have demonstrated the ability to manufacture autoclave quality structures with ISC. A key challenge facing manufacturers is addressing throughput speeds to achieve desired production rates.

The ability to co-bond thermoplastic stiffeners with ISC eliminates the need for secondary operations traditionally required to fasten stiffeners to skins..

This paper reviews worldwide efforts to develop ISC, Automated Dynamics current capability to manufacture autoclave quality structures using ISC, and future work needed to meet throughput targets.

Automated Dynamics has been manufacturing thermoplastic composite structures using in-situ automated fiber placement for more than 30 years. In the intervening decades the automotive industry has embraced thermoset and thermoplastic composites but failed to recognize the advantage of in-situ consolidation. Programs such as FoT and WoT strive to develop the technology necessary for high rate production in the automotive industry using thermoplastic composites with the current focus on compression molding of preformed skins and reinforcement elements. While this is proving to be a viable method to manufacture OoA thermoplastic composite structures, it is sub-optimal. The optimal manufacturing method would be additive manufacturing of high performance TPC structures.

In-situ automated fiber placement of thermoplastic composites is additive manufacturing and has been used for decades to produce high performance composite structures for automotive, defense, industrial, and other applications. Automated Dynamics current state of the AFP work cell uses a closed loop Laser Heating System to melt bond the incoming thermoplastic material to the previous ply at a high rate of speed. The resulting structure has autoclave equivalent consolidation and porosity.

This paper surveys the capabilities of Automated Dynamics current state-of-the-art in-situ automated fiber placement work cell for processing autoclave quality thermoplastic composites structures via a true OoA process.

## Review worldwide efforts to develop ISC

Automated Dynamics was one of the first to develop what is now known as ISC of TPCs in the mid-1980s.[1,2] Automated Dynamics and researchers around the world have continued development of the technology using hot gas,[3] flame,[4] IR,[5] and laser heating. Laser heating research was mostly performed using $CO_2$ lasers[6] and laser scanners[7] which resulted in slow processing rates. Most polymers are opaque to the 10.6 µm wavelength emitted by $CO_2$ lasers which concentrates absorption at the surface leading to polymer degradation at high irradiance.

The early exception was a direct diode laser developed by John Haake of Nuvonyx (now Titanova) in the late 1980s for ISC development at MacDonnell Douglas (now Boeing).[8] Polymers are transparent to the 940 nm wavelength of diode lasers allowing laser energy to penetrate the prepreg tape and heat the carbon fibers rather than degrading the surface polymer.[9] In the intervening decades improvements have been made in high energy direct diode, fiber,[10] and VCSEL[11] lasers making them an economical choice for ISC. Heraeus has developed a high energy flash lamp product named humm3 that produces broad spectrum light using a flash lamp for an eye-safe alternative to IR lasers.[12]

Airbus' commitment to focus on TPCs for the next generation commercial aircraft is driving renewed ISC research globally. FIDAMC,[13] Fraunhofer IPT,[14] AMAC,[15] and others are demonstrating different approaches to ISC. FIDAMC reports near autoclave equivalent properties with ISC. Stokes-Griffin reports 98% of autoclave SBS values at 400 mm/sec process rate.[16] Automated Dynamics is achieving similar results with our laser heating system and are working on improved prepreg tapes,[17] higher process rates, lower voids,[18] and reduced CTE induced warpage.[19]

## Automated Dynamics current capabilities

Automated Dynamics has been using ISC to make thermoplastic composite parts for the past 30 years. We sell thousands of kilograms of structures made using our in-situ consolidated process every year. For most of our history we have used a Hot Gas Torch (HGT) and a heated compaction roller to melt and consolidate the thermoplastic composite material as shown in Figure 1.

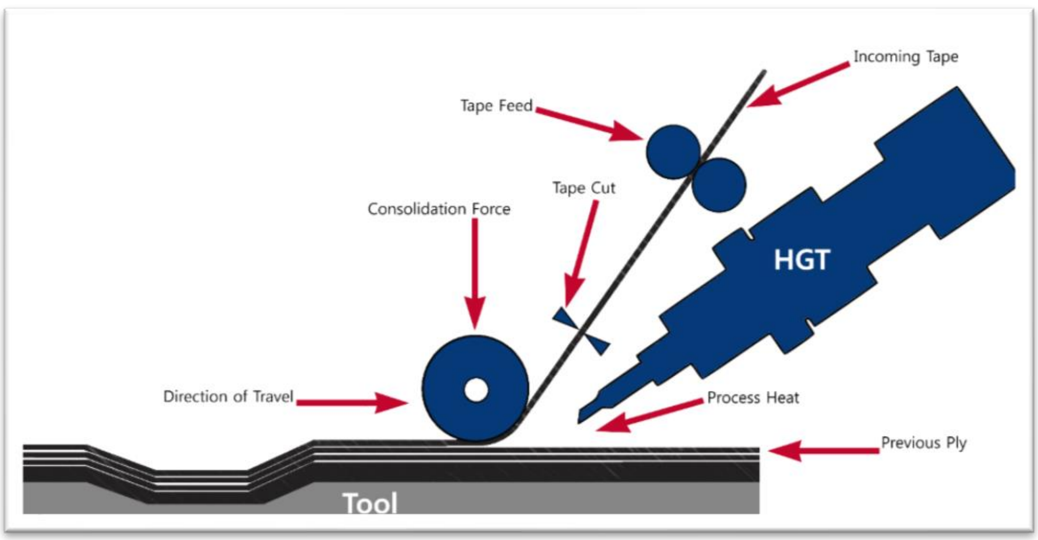


*Figure 1- In-situ consolidation process diagram*

The ISC process uses unidirectional fibers pre impregnated with thermoplastic polymer. This material is often referred to as tape. The prepreg tape is often made in wide rolls (6" to 12" wide) and then the roll is slit to a narrow width such as ½" wide. The geometry and the desired ply angles of the part dictate what width tape gets used. The prepreg can be slit as narrow as 1/8" wide for complex, small parts. The prepregs are generally about 0.005" thick to 0.010" thick. Most thermoplastics can be used to make composite tape. A wide range of fibers can be used to make composite tape too. This means there is a huge number of combinations of composite tapes that can be made to meet the demands of any application. All these thermoplastic prepregs can also be ISC using AFP.

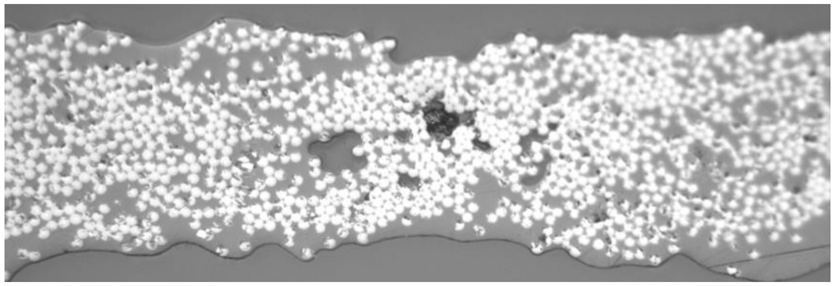

*Figure 2- Micrograph cross section view of unidirectional thermoplastic prepreg.*

We are always striving to improve the quality of parts that can be made using our ISC process and to improve the production rate. We have developed many new processing methods over the years and our latest leap has left the HGT and the heated compaction roller behind in favor of a Laser Heating System (LHS) and a cooled compaction roller. These new developments have increased the quality of our ISC process to a point that meets current aerospace requirements for void volume, crystallinity and process rate.

The LHS is closed loop controlled and the area it heats is very precise. This has allowed us to use a Silicone compaction roller with certain polymer prepreg. Our normal ISC process uses rigid steel compactions rollers to press the incoming material against the substrate. The steel compaction roller works great for hoop plies and constant diameter parts but it has its limitations. In order to place off angle plies such as 0° and 45° plies we use what we call an apple core radius roller. The required radius of the roller is driven by the ply angle and the diameter of the part being processed. The radius roller provides pressure across the width of the tow being placed. Parts made with these rollers are fully consolidated but it takes time to change the rollers during processing which can slow down production of the composite structure. The rigid radius rollers also limit the change in curvature that a part can have within one ply. A part with double curvature is very challenging to process with a rigid roller.

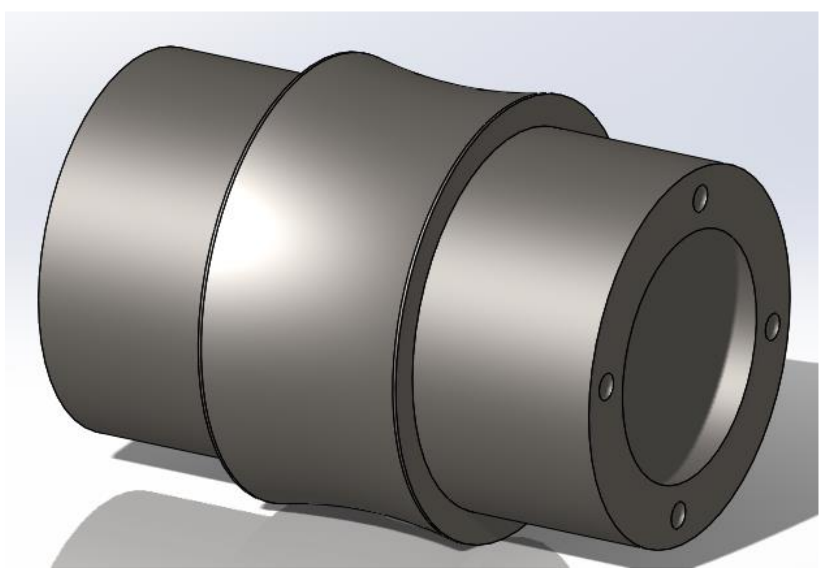

*Figure 3- Radius compaction roller*

A solution to this problem is to use a conformable compaction roller. However, conformable materials degrade at the high temperatures that many engineering thermoplastics require for processing. Silicone compaction rollers can be used to ISC process thermoplastic prepregs that have relatively low melting points such as nylon, PP, PE and PET. The process temperature of nylon is right at the limit of where silicone starts to degrade. We have made carbon fiber nylon parts using a silicone roller and our LHS. The parts made with the silicone roller have been tested to verify that full consolidation has been achieved. The conformable roller allows for parts with complex geometries to be made. It also improves the through put by eliminating roller changes and it enables wider material to be used to make the part.

*Figure 4- Part made with silicone compaction roller showing 45° ply during fabrication*

## Laser Heating System to Process High Temperature TP Composites

Automated Dynamics started developing our LHS in 2010 and we have been using it to make production parts since 2015. We started selling our LHS hardware and software to third parties starting in 2012. The LHS uses closed loop control to maintain the desired temperature in the laser irradiated area. This control allows us to put a large amount of energy into a small area which enables ISC of high temperature TPCs at high process speeds. The closed loop control allows for the processing of CF/PEEK and lower temperature TPCs in addition to the processing of thermoset composites.

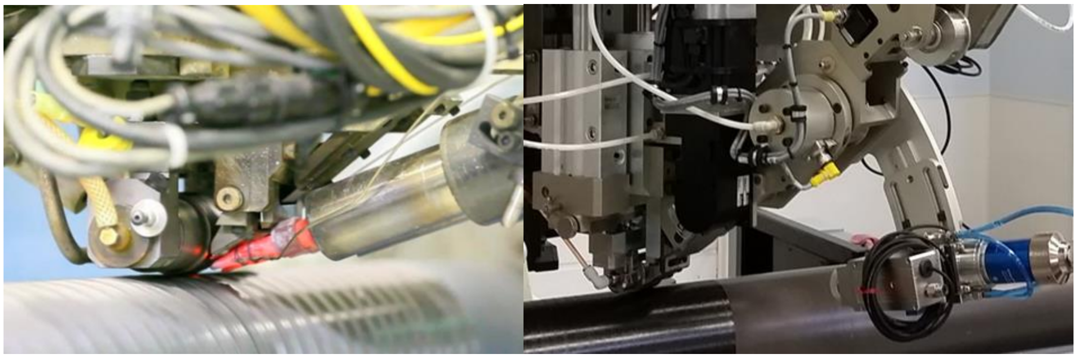

*Figure 5 - HGT ISC (left) and LHS ISC (right)*

*Low void volume*

Void volume is a critical specification for composite structures. CMH-17 specifies less than 2% voids for primary aircraft structures. A void in a composite laminate acts as a stress riser and is a potential site for crack initiation leading to failure, particularly in fatigue. Thermoplastics are more ductile than thermosets resulting in greater damage tolerance and fatigue life[20] making them less sensitive to voids. However, CMH-17 currently makes no distinction between thermosets and thermoplastics relating to void volume so the requirement is less than 2%. Processes such as autoclave and compression molding provide high pressures and long soak times for voids to compress and migrate out of the laminate. ISC allows milliseconds in the bond zone at high process rates making it more difficult to manufacture low void laminates.

Standard tests for void volume involve ASTM D2734 (combustion) and ASTM D3171 (acid digestion). However, these tests are known to have an accuracy of +/-2% for void volume based on the interferences listed in each standard. This leads to measurements of void volume that can commonly have negative values when using these methods. For TPCs, both void volume tests have more draw backs than for thermoset material. The main drawback is that the void volume is calculated using the density of the as-processed polymer. The density of the as-processed semi-crystalline thermoplastic polymer is dependent on the crystallinity of the polymer while thermoset resin doesn't crystallize. Another such drawback is that engineering grade thermoplastics are harder to dissolve or burn away from the fibers due to their strong resistance to chemicals and their poor combustibility. Automated Dynamics has found that ASTM D3171 Procedure B Method 1 gives the most consistent results for void volume of high grade engineered thermoplastics such as PEEK. However, this standard can't be used as a stand-alone because the as processed crystallinity of the polymer greatly affects its density. Having the incorrect density has a large effect on the calculated void volume of the sample. To minimize this affect we have performed ASTM D3418 on a sample from the same part to determine the as processed crystallinity which is then used to determine the density of the polymer in the sample that is used in ASTM D3171. All these variations are compounded even further by the variation in density of the fiber itself. According the fiber supplier Hexcel the density of the carbon fiber can vary from 1.75 to 1.81 g/cm$^3$. This means that the void volume varies as much as 3% based on the fiber density alone.

Running ASTM D3171 and ASTM D3418 to determine the void volume of a part is very expensive and time consuming. Another option is to use Micro CT scans to measure void volume. This approach uses a grayscale to define areas of different densities so it has its own limitations but it is less expensive, faster, and non- destructive. It also gives the exact location and size of each void which ASTM D 3171 can't do. To get that information microscopy would have to be performed on a cut, mounted and polished sample. Mounting and polishing has its own limitations the main one being that only voids on a 2D surface can be seen. There is also the added cost and lead time associated with performing another test.

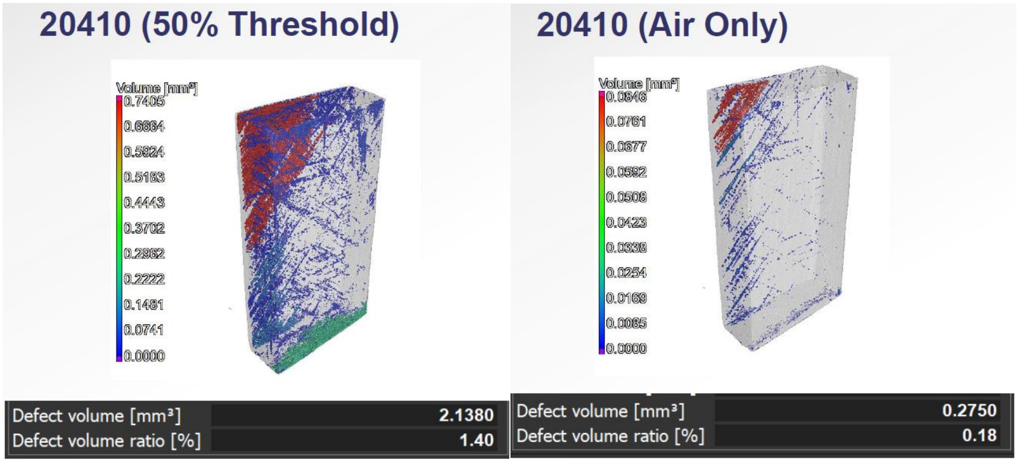


*Figure 6 – Micro CT images showing low density regions (left) and air only regions (right)*

Automated Dynamics has made quasi-isotropic flat panels using CF PEEK from Solvay (prepreg void volume 5%) using our LHS and ISC. The panel was 24 plies thick with a balanced and symmetric layup $[+45/-45/0/90]_{3S}$. Using ASTM D3171 Procedure B Method 1 the average void volume from these test samples was 1.92%. This means that not only does our in-situ process not induce many voids between plies (interlaminar voids) it also drives the voids out of the raw material (intralaminar voids). These parts were processed at 254 mm/sec using 12.7 mm wide material which equates to an estimated process rate for large parts at about 2.0 kg/hr.

Automated Dynamics has compared void volume results determined by running ASTM D3171 and ASTM D3418 to the void volume results from Micro CT and found that the results correlate strongly. In the latest round of testing Automated Dynamics has fabricated flat panels made with CF/PEKK using our LHS to ISC the parts. The void volume was analyzed using Micro CT and found to be 1.40%.

The Micro CT scan used can detect air voids as small as 15 microns across. Any void smaller than 15 microns gets detected by using a 50% threshold for low density regions. The sample tested had only 0.18% void volume that were 15 microns or larger. The remainder of the 1.40% void volume is voids that are smaller than 15 microns.

*High crystallinity*

The as processed crystallinity of a part is determined using the first DSC heat cycle. The second heat cycle gives the crystallinity of the polymer for a controlled cooling rate. Using DSC to determine the crystallinity isn't an exact science since the points on the graph where the heat of fusion is integrated over is determined by hand. This leads to different testing facilities reporting drastically different percent crystallinity for the same samples. Two samples from the same part where sent to two different labs and the first lab calculated the percent crystallinity to be 34.89% while the second lab calculated the percent crystallinity to be 29.43%. These parts were made with our HGT process and have full crystallinity as shown in Figure *7*.

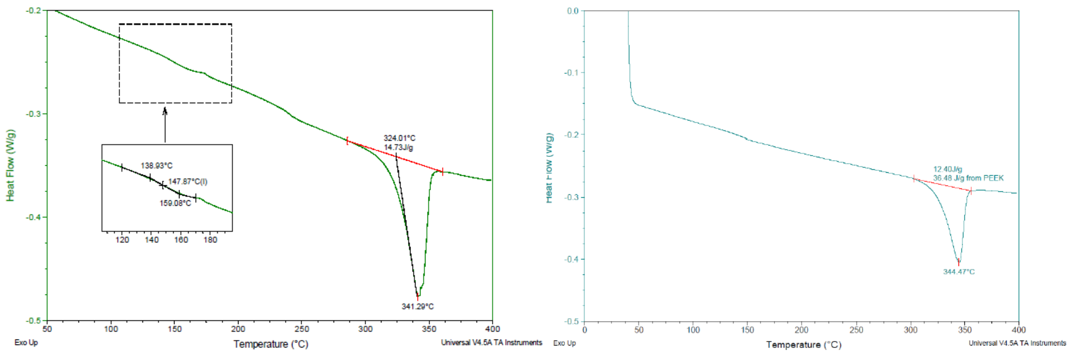


*Figure 7: DSC plot from 1st lab for SN 16177 (left) and DSC plot from 2nd Lab for Sn 16177 (right).*

This full crystallinity is possible due to the combination of the large Heat Affected Zone (HAZ) created by the torches and the added heat energy from the heated compaction roller. The heated compaction roller is held above the melt temperature of the polymer but below its degradation temperature. Every ply that is laid down gets exposed to this large amount of heat which penetrates through the current ply being placed to previous plies. This constant heating above the Tg and cooling creates a fully crystalized polymer. However, the HGT process has a lower production rate than the industry desires at about 0.73 kg/hr. using 12.7 mm wide prepreg.

We have been optimizing our LHS to produce parts with a high level of crystallinity at our current production rate of 2.1 kg/hr. These advancements have enabled us to achieve in-situ processed crystallinity of 28.85%. Due to the variation is crystallinity results from DSC we could argue that these parts are almost fully crystallized (34% is the accepted standard). The DSC plot gives a more consistent gauge of the level of crystallinity than the calculated number. A sample is fully crystalline when there is no exotherm after Tg due to the enthalpy of crystallization as shown in Figure *7*. However, the DSC plot for the LHS sample shown in Figure *8* has an exotherm after Tg. While this exotherm is 5 times smaller than a sample made with the baseline LHS it shows that we still haven't reached full crystallinity as we did with the HGT samples.

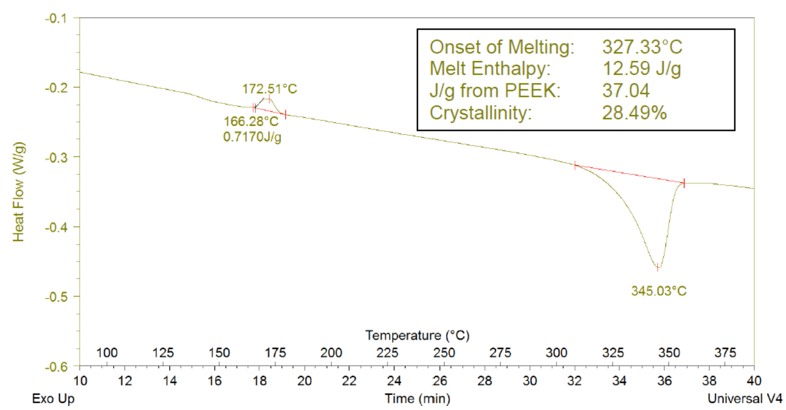


*Figure 8: DSC of part made with LHS. Has exotherm after Tg indicating it isn't fully crystallized.*

*High process rate*

Currently we are LHS processing 12.7 mm wide prepreg, however our laser welding head can accommodate an integrating optic large enough to process 25.4 mm wide prepreg. Using 25.4 mm wide prepreg would increase the production throughput to over 4.1 kg/hr. Another way to increase the throughput is to use thicker prepreg to make the composite structure. We have successfully in-situ processed CF/PA6 with the LHS that is 0.28 mm thick. If the thicker tape were combined with the 25.4 mm width, then the process rate would increase to 8.2 kg/hr.

The process rate can be increased further by using wider prepreg. Processing wider prepreg on large structures can be done as proven by our 76 mm wide automated tape placement head. A prepreg tape this wide would require multiple laser welding heads to cover the width of the material. The 76.2 mm process area doesn't have to be a single prepreg tape either. We have multi tow processing heads that have individual tow control with the ability to add and drop tows while processing. These different features could be combined to create a processing head capable of making large parts with varying geometry and build up regions. We have put a laser welding head with a 25.4 mm optic on our 4 x 6.35 mm individual tow control thermoset head for a customer to process thermoset material at very high rates on the order of 1m/sec. This results in a process rate of 16.3kg/hr. with a single process head on a single robot. This rate, like the others referenced in this paper assume an off the part time of 5% and a down time of 15%. Our AFP equipment uses articulated arm robots that allow multiple robots to work on one part at the same time which is another way to increase throughout to meet the aerospace desire to in-situ process 30 kg/hr.

## Future work to meet throughput targets

There are more complex ways to increase throughput to meet the requirement.  These methods need to be developed but the most promising ones are based our current limitations that we see in the ISC process. ISC of thermoplastic composites doesn't rely on reptation theory to thermally entangle the polymer chains between plies like the autoclave process does. According to classic reptation theory the polymer entanglement takes longer than the time the composite material is under compaction during ISC of thermoplastic composites. Mechanical testing of in-situ consolidated composites proves that polymer chain entanglement does occur. The theory that best explains this phenomenon is shear mixing.  Since ISC is a dynamic process it causes the molten polymer to flow and mix together. This physical mixing of the polymer layer of the two plies allows for ISC. Increasing the shear mixing increases the bond interlaminar bond strength of the composite structure.

The main goal of increasing shear mixing is to increase bond strength so the process speed can be increased and there are several ways to achieve this. One of the simplest is to add extra polymer to the nip region. This can be achieved two ways, by adding extra polymer to the nip region in-process or by making prepreg with a very thin layer of resin on the surface. Our 30 plus years of experience has shown us that the polymer layer needs to be about 0.0127 mm thick. This observation is based on trials we have done with composite materials from different prepreg manufacturers. Material that we are able to process at higher speeds has more polymer on the surface than materials than materials that successfully process at lower speeds. Currently no prepreg manufacture has demonstrated a consistent thin layer of polymer on the prepreg surface. Some manufacturers' prepreg has extra polymer on the surface but it isn't consistent in thickness or distribution along the length and across the width of the material. Other manufactures' prepreg has a very consistent lack of polymer on the surface. The goal is to get prepreg that meets our stringent requirements for polymer distribution and overall polymer content of the prepreg.

Another way to improve shear mixing is to add small amounts of neat resin into the HAZ creating a weld bead much like in metal welding.[21] Controlling the amount of added resin in real time has the added advantage of filling voids at ply drops and ply boundaries.

Higher process temperatures can be used in ISC because the extremely brief time (milliseconds) at temperature for the polymer which reduces viscosity without thermal degradation of the polymer. Consider that Figure 5 below shows TGA data for PEEK to 20° C/min whereas modern ISC with laser heating yields heating rates closer to 20,000° C/second. Most importantly, ISC is a dynamic process that results in shear thinning and squeeze flow if the process and prepreg is properly designed. This is not a new concept, injection molding of high performance polymers such as the PAEK family would not be possible without shear thinning and rapid injection.

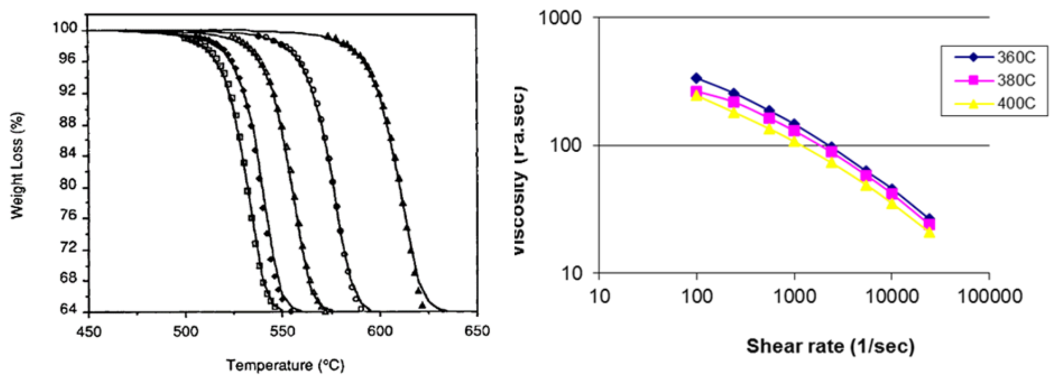


*Figure 9 - TGA data for PEEK at heating rates from 0.7° C/min (□) to 20° C/min (▲ ) (left)[22] and shear thinning of PEEK (right)[23]*

Internal studies performed on our equipment has shown there is a way to increase polymer shear mixing without using ideal prepreg or added polymer. This method uses vibration to cause shear thinning and shear mixing and polymer chain entanglement. Using this process, we were able to maintain the ILSS from NOL samples following ASTM D2344 at almost double the processing speed.

## Improvements to Laser Control

Another way to increase the throughput of ISC is to improve temperature control of the HAZ. Currently our LHS uses closed loop controls to maintain temperature of the HAZ at the desired temperature. However, this control system is simple and uses a spot pyrometer to measure the temperature. A future goal is to use a FLIR camera and an advanced software to better control the temperature of the HAZ. Currently one of our main limitations on process speed is flare ups caused by exposed fibers in the prepreg absorbing too much energy. The FLIR with the advanced controls would enable higher energy input and lower the occurrence of flare ups. This increase in laser energy has been correlated with increased process speed in our internal trials.

A more advanced option to increase laser control is to use a Vertical Cavity Surface Emitting Laser (VCSEL) to provide different amounts of laser energy to different portions of the laser irradiated area. This would allow the closed loop control system to limit laser power in areas where a flare is occurring while maintaining laser power in areas that can handle the extra energy without overheating.

## Conclusions

After more than 30 years of development TPCs are finally being widely used in aerospace applications and ISC is finally recognized as a viable method for the manufacture of aerospace quality structures. The next challenge is to demonstrate high rate production for commercial airliners. Innovative work by Automated Dynamics and researchers around the world are converging on optimal solutions to produce aerospace quality TPC structures with ISC at high process rates.

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