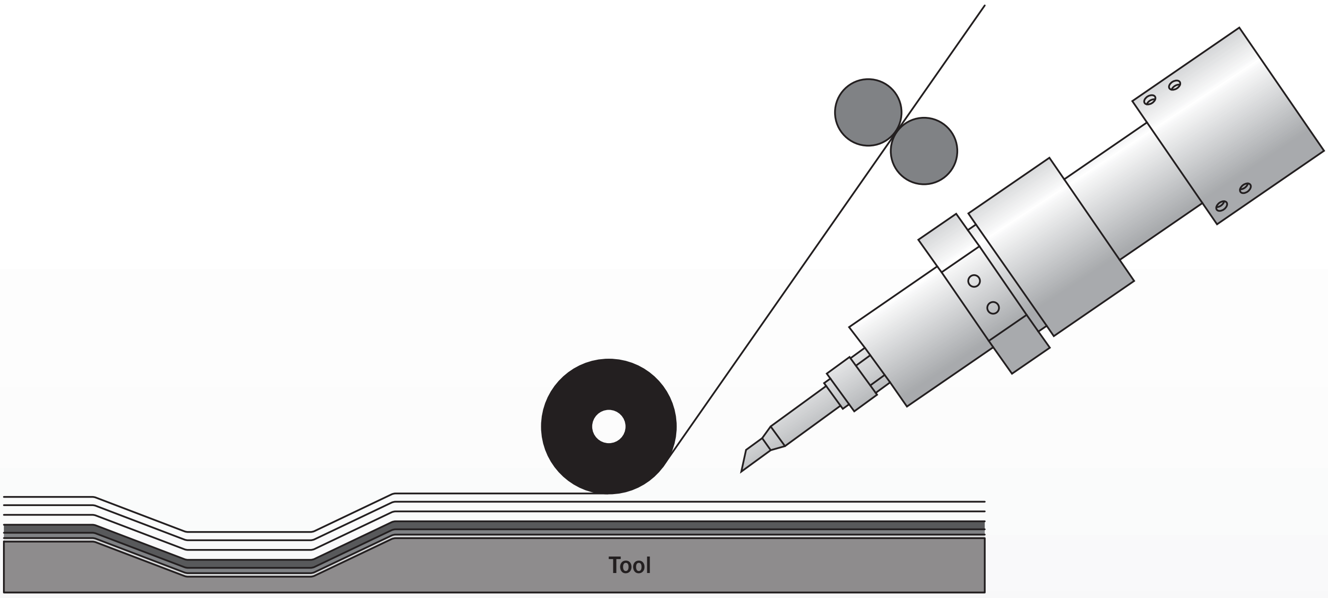
TRELLEBORG SEALING SOLUTIONS

Automated Fiber Placement of Thermoplastic Composites

A COST EFFECTIVE OUT-OF-AUTOCLAVE PROCESS



1. INTRODUCTION

Automated Fiber Placement of Thermoplastic Composites: A Cost Effective Out of Autoclave Process

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The advantages of thermoplastic composites are well known and their use continues to grow as a result. Many fabrication technologies have been developed with the general goal of automated production of high performance structures using Thermoplastic Composite (TPC) materials. The most versatile of these technologies is in-situ consolidated TPC by Automated Fiber Placement (AFP), a true Out-of-Autoclave (OoA) Additive Manufacturing (AM) process.

Although TPC AFP is a mature technology that has been used in serial production for over 30 years, recent technical papers have cast some doubt. Several examples of high performance in-situ consolidated TPC AFP structures will be presented to dispel any of these doubts. This paper clarifies erroneous technical assumptions in the existing literature, describes the current state-of-the-art of in-situ TPC AFP, describes the author's current research and outlines future advancements.

2. ADDITIVE MANUFACTURING FOR COMPOSITES

Just as the machine tool industry has progressed from manual operations to automated CNC machining centers, the composites industry is moving from hand lay-up to automated processes. Unlike the machine tool industry that relies on subtractive processes, composites require additive processes.

In order to take advantage of the directional strength characteristics of composites, the fibers must be placed layer-by-layer in orientations and patterns that optimize their strength and stiffness for a given application.

Additive manufacturing processes for metals and polymers such as Laser Additive Manufacturing (LAM), Direct Metal Laser Sintering (DMLS) and Ultrasonic Additive Manufacturing (UAM) are capable of manufacturing complex structures directly from a 3D CAD model with very little wasted materials.

Designers can create a model, “print” it and have a functional part in minutes. Similar processes are needed for composites.

3. AUTOMATED FIBER PLACEMENT (AFP)

AFP is an additive manufacturing process for composites. There are now many manufacturers of AFP equipment for thermoset composites in production around the world. The benefits of AFP include:

- Material savings
- Labor savings
- Quality improvement
- Accurate fiber placement at any angle
- Automatic debulking
- Reduced manufacturing space
- Reduced assembly costs

The benefits of AFP are well understood and the technology is now established. We finally have an automated process for composites comparable to CNC workcells for the metalworking industry. However, with thermoset composites there is still a curing step that requires a manual bagging operation and an expensive autoclave cycle. The autoclave is a bottleneck in the manufacturing process and there are efforts around the world to develop Out-of-Autoclave (OoA) processes. What is needed is a process that eliminates the energy intensive, time consuming, bottleneck of bagging and curing thermoset composites.

4. THERMOPLASTIC COMPOSITES (TPC)

TPCs are melt processable and do not require a cure cycle. In addition, thermoplastic composites have other advantages over thermosets including:

- Exceptional fatigue resistance
- Extreme toughness/damage tolerance
- Superior solvent and chemical resistance
- No toxicity/hazardous chemical issues
- No cure chemistry, refrigeration or out-time considerations
- Recyclable
- Excellent FST (Fire, Smoke, Toxicity) stability
- Hydrolytic stability
- Stable Tg – even under hot/wet conditions
- Low water absorption
- Low coefficient of friction
- High abrasion resistance
- Repairable (can be machined and reprocessed via melt bonding)

Even with myriad advantages, thermoplastic composites have been slow to gain acceptance. Thermoplastic resins are inherently more viscous than thermoset resins due to their high molecular weight, which makes it more difficult to wet out the reinforcing fiber. However, thermoplastic resins (especially commodity resins such as PE, PP and PA) are less expensive. Ultimately, the material property advantages and lifecycle cost reductions will favor TPCs just as has already occurred for thermoplastics in general. As is the case with all material systems, initial costs are high but costs decrease as the sales volume increases due to economies of scale. This has certainly been the case for carbon fiber and thermoplastic composites. Major capacity expansions are planned by the primary suppliers and new suppliers are entering the market at an increasing rate.

A major advantage of thermoplastics over thermosets is cycle time reduction. Just as injection molding, extrusion and other process technologies have revolutionized neat resin and short fiber reinforced TP manufacturing, similar processes are coming online for continuous fiber reinforced TPCs.

Press and diaphragm forming methods such as promoted by Teijin and others are lowering consolidation costs for mass produced TPC structures. Although this is an improvement over autoclave processing, setup and tooling costs are only suitable for large production runs and a preform must still be manufactured for subsequent consolidation. As we enter the age of mass customization, we need flexible means to lay-up and consolidate TPCs.

5. TPC AFP

5.1 Background

Automated fiber placement with thermoplastic composites has been around for about 25 years. Much of the early development was done in the US under ARPA (Advanced Research Projects Agency) for the MACSS (Manufacture of Advanced Composite Submarine Structures) program. This program was a pioneering effort that demonstrated the promise of TPC AFP and revealed challenges for the future. The challenges were primarily high quality, low cost prepreg and rapid production rates. Despite reports to the contrary, much progress has been made in the past few decades.

5.2 State-of-the-Art

Misconceptions vs. Reality Concerning TCP AFP

There have been several papers published in recent history that claim in-situ TPC AFP is not a viable process because the process speed must be slow in order to achieve consolidation. This misconception derives from classical polymer reptation theory originally suggested by de Gennes. The general concept is that melt bonding of polymer surfaces (including TPC prepreg) involves three stages – intimate contact, molecular diffusion (reptation or autohesion) and consolidation. Intimate contact involves bringing the two surfaces together under heat and pressure such that the polymer matrix of each surface is in direct contact. Once intimate contact is achieved, the polymer chains diffuse between the two layers via thermal vibrations and entangle to form a bond. Finally the bond zone is cooled under pressure and a cohesive (TP fusion) bond is achieved.

The general perception is that in-situ consolidation must proceed according to classical reptation theory as realized in autoclave consolidation. Indeed, if one takes this approach, you would end up with a long soak time that demands a slow process rate and an unwieldy mechanism as illustrated in Figures 1 and 2.

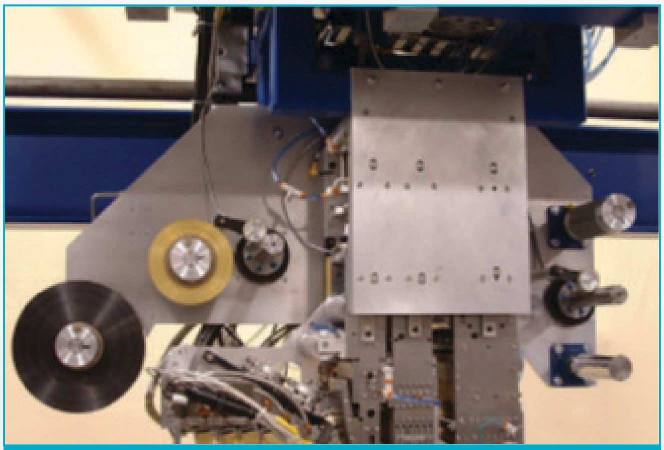

Figure 1 - Continuous autoclave style process

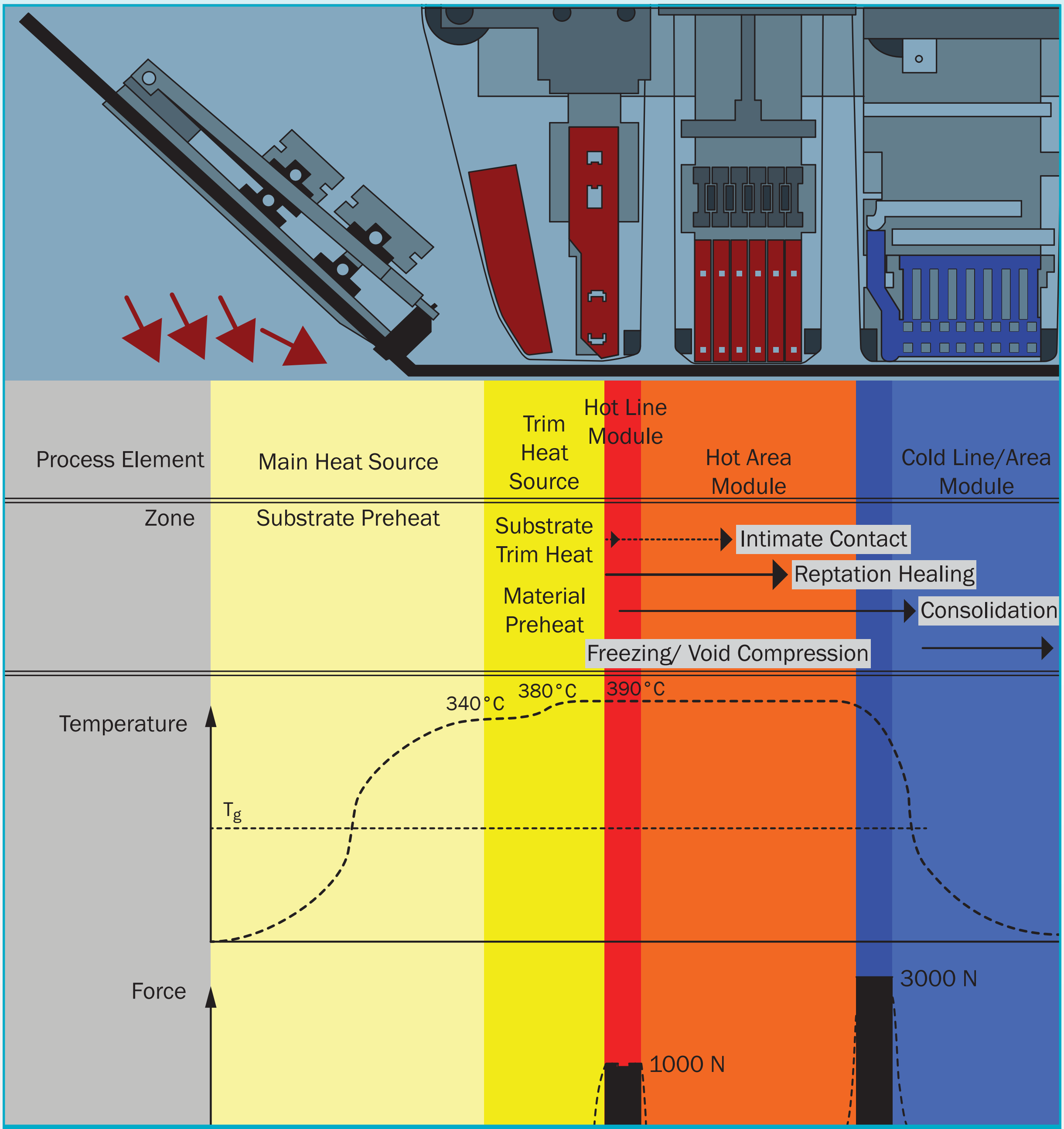

Figure 2 - Continuous autoclave style process

The process Trellborg Sealing Solutions employs for TPC AFP relies on a small Heat Affected Zone (HAZ) to heat and bond the incoming tape to the laminate with a single compaction device. This allows for a compact head design providing the ability to fabricate complex structures. An early TPC AFP head design is illustrated in Figure 3.

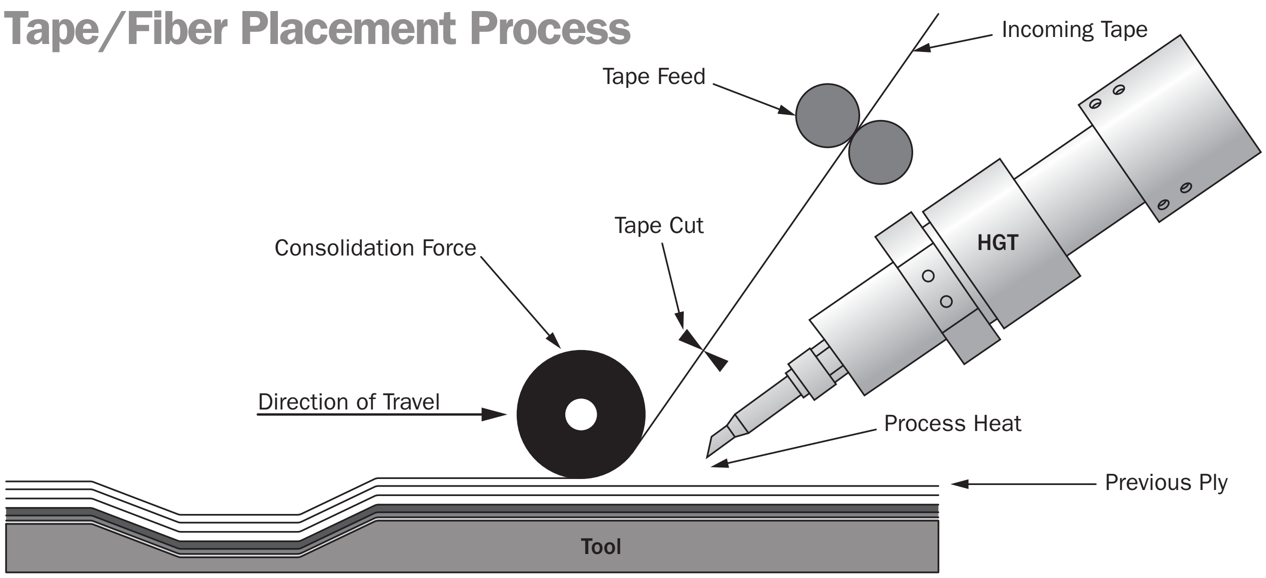

Figure 3 - TP AFP Process illustration with a Hot Gas Torch (HGT)

The IR image below shows the hot gas process in operation. The image is of the nip region from the point of view of the "Process Heat" arrow in the above diagram.

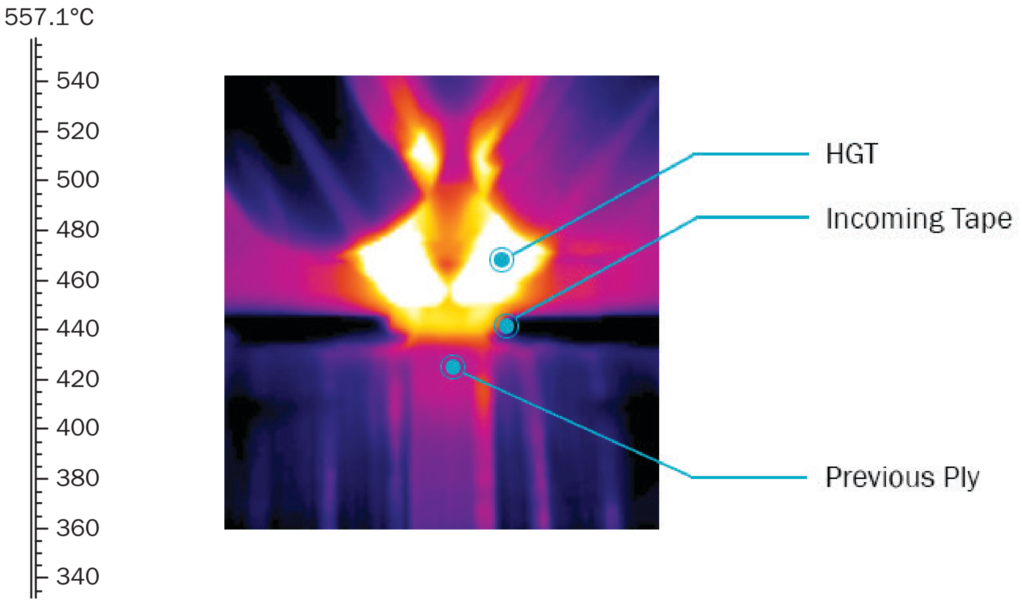

Figure 4 - Thermal image of TPC AFP, view into nip

Notice in Figure 4 that the prepreg tape in the nip region is heated to around 500 °C using heated nitrogen (not visible in the IR image). The relatively small HAZ demands high energy input in order to bring the surfaces up to the desired temperatures quickly to enable high process throughput. High pressures are not required as several studies have shown that pressure is the least important of the primary bond parameters of temperature, pressure and time (process speed) for interfacial bond strength, although there is a correlation to reduced void content with higher pressure in at least one model.

The short time in which the bond zone is maintained under the compaction device at high throughput rates does not allow as much time for polymer chain diffusion as classical reptation theory would predict for ideal bonding. However, these models have not incorporated all factors such as shear thinning of the polymer due to the extremely rapid application of pressure, polymer flow in the nip area and other factors which greatly increase polymer interdiffusion over the classical (autoclave style) case of static surfaces in intimate contact. We must be cognizant of Bonini's paradox: the only truly accurate model is the process itself.

Why is it that models have not accurately reflected results that have been achieved for decades in serial production of TPC AFP structures? For example, Nicodeau and Cinquin develop an elegant model for hot gas TPC AFP but claim less than ideal interfacial strength with the chosen macromolecular diffusion and "end life" (polymer degradation) criteria. However, macromolecular diffusion is modeled as in autoclave processing and does not include shear thinning or polymer flow effects. The graph below illustrates the dramatic shear thinning that occurs in PEEK polymers even at low process temperatures.

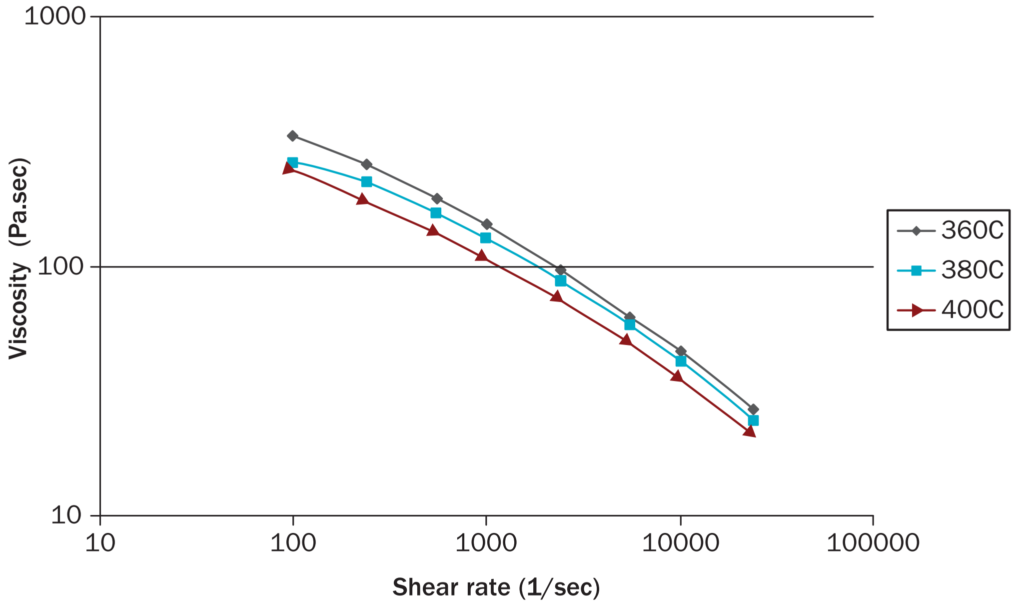

Figure 5 - Shear Rate vs. Viscosity for PEEK 150G[8]

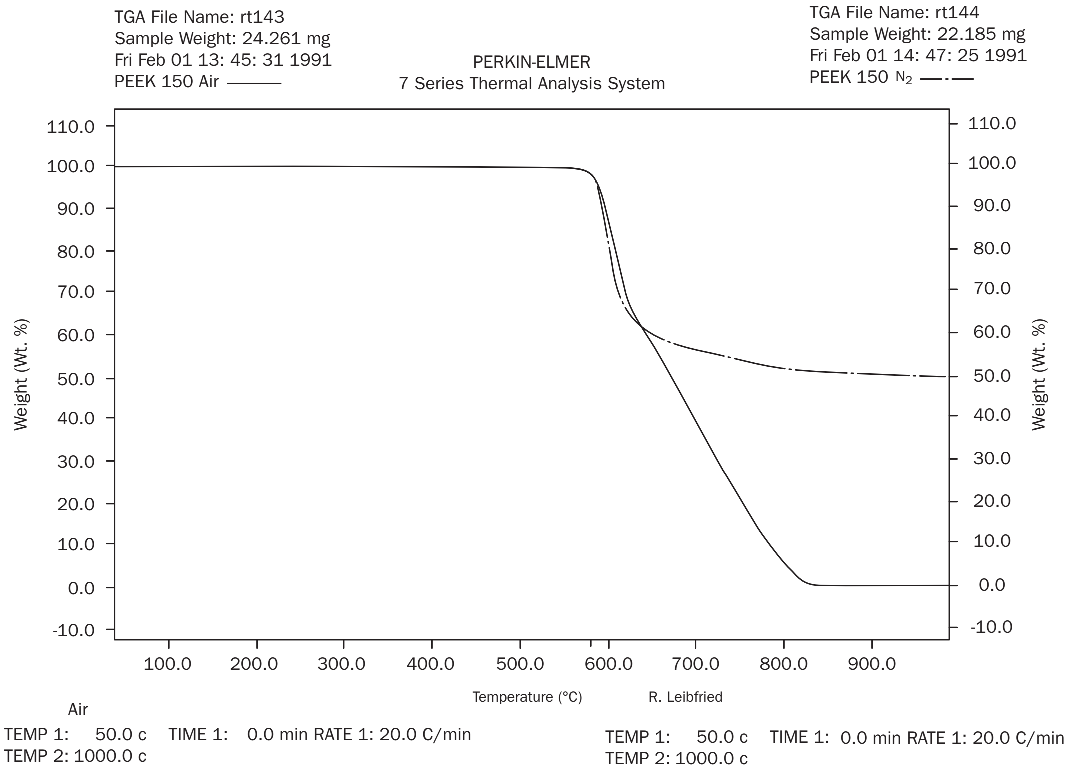

Figure 6 - TGA data for PEEK in nitrogen and air

Polymer degradation is likewise overstated. For example, DeVries claims a maximum processing temperature of 400 °C. The TGA data above show no degradation until 550°C in nitrogen or air (typical TPC AFP uses an inert environment such as nitrogen).

Consider also that the TGA scan (Figure 6) takes 10 minutes to go from 350 °C to 550 °C with very little weight loss whereas the polymer spends milliseconds in the HAZ at typical modern TPC AFP process rates. Weight loss above 550 °C is due to chain scission, primarily in the carbonyl linkage leading to crosslinking reactions.

Studies conducted with composites (fiberglass and especially carbon reinforced PEEK) show significantly reduced degradation over the neat PEEK data shown above. Another important feature of a small HAZ is low residual stress.

Unlike autoclave consolidated laminates, in-situ TPC AFP structures are consolidated a layer at a time. CTE (Coefficient of Thermal Expansion) effects are limited to the HAZ and are thus distributed through the thickness of the laminate rather than concentrated at the surfaces. This is particularly important for thick laminates, such as flywheels.

In semicrystalline polymers, it is generally advantageous to achieve a high degree of crystallinity to improve solvent resistance and reduce creep (at the cost of lower ductility). It would seem apparent that the rapid cooling as the laminate leaves the HAZ would result in low crystallinity in semi-crystalline polymers such as PEEK.

However, crystallinity of 25% to 30% is achieved in the first layer and can be as high as 34% in the laminate as subsequent plies raise the temperature in the laminate enough to promote further crystallization. Thus it is possible to achieve crystallization levels approaching the maximum crystallinity level “of 37% at many hours at the ideal crystal growth temperature” with TPC AFP.

5.3 Current Developments

Hot gas heating as developed by Trelleborg Sealing Solutions has been the industry standard since 1986 due to its low cost and wide process window. Alternate heating methods such as flame, ultrasonic, IR, induction and laser have been evaluated by Trelleborg Sealing Solutions and others. The most promising is laser heating due primarily to its high energy density, efficiency and rapid response time. High energy lasers are becoming economically feasible due to modern solid state laser diodes and wide acceptance in the metalworking industry.

Much of the recent development in TPC AFP has been aimed at producing preforms for subsequent consolidation via autoclave, press, diaphragm forming, stamping or other methods.

While this approach may be appropriate for certain applications, it is not ideal and a true additive manufacturing technology is desired. Closed section and thick section structures are particularly problematic for this multi-stage consolidation approach due to fiber waviness and residual stress induced during debulking in post processes.

The solution lies in thinking beyond the paradigm of classical reptation theory as embodied in traditional autoclave style processing of thermoplastics.

With laser heating, the temperature in the bond zone can be precisely controlled in real time and molecular diffusion can be achieved without long soak times and compaction pressure can be maintained throughout the bond cycle even at high process rates. Methodologies to address these issues will appear in the patent literature within the coming year.

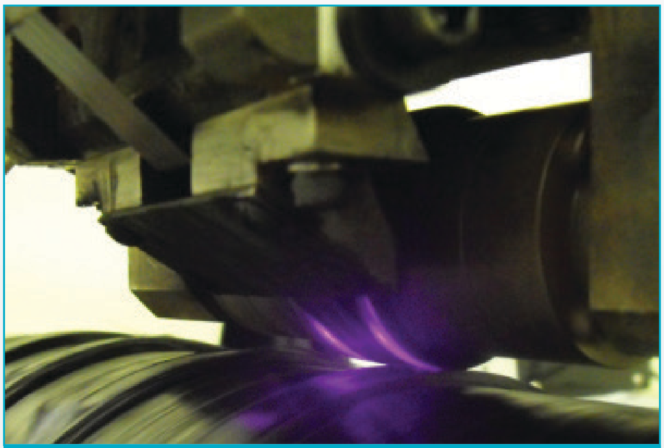

Figure 7 - Laser heating in TPC AFP

6. SERIAL PRODUCTION USING IN-SITU TPC AFP

Even without recent technological advances, TPC AFP has been used for serial production for over 30 years. These applications include industrial, oilfield, fluid handling, aerospace and defense. A simple example of the widespread application of TPC AFP is the pipe shown below. TPC AFP is used in-line with extrusion to reinforce the bell on corrugated pipe.

These pipes are in production throughout the world. Products fabricated using TPC AFP that are in serial production are too numerous to mention but a few examples from oilfield, fluid handling and other industrial applications are illustrated in Figures 8 through 11 and Photos 1 through 8.

Figure 8 - TPC AFP is used in-line

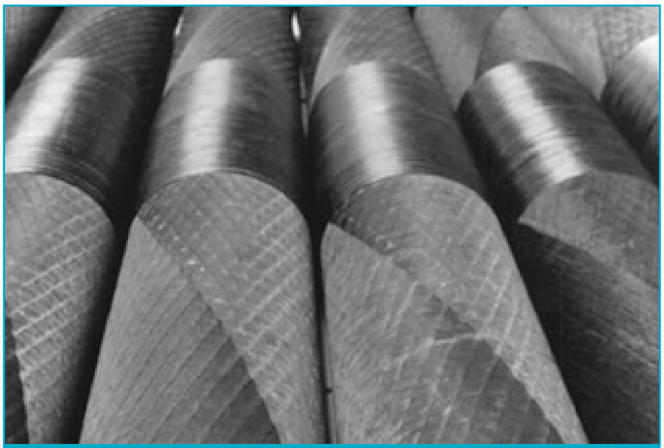

Figure 9 - Oilfield

Figure 10 - Fluid handling

Figure 11 - Industrial applications

Photo 1

Photo 2

Photo 3

Photo 4

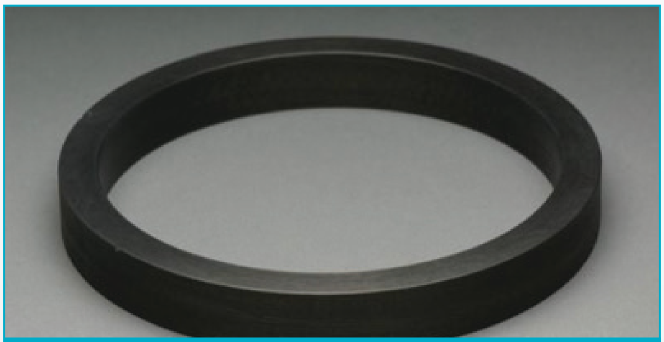

Photo 5

Photo 6

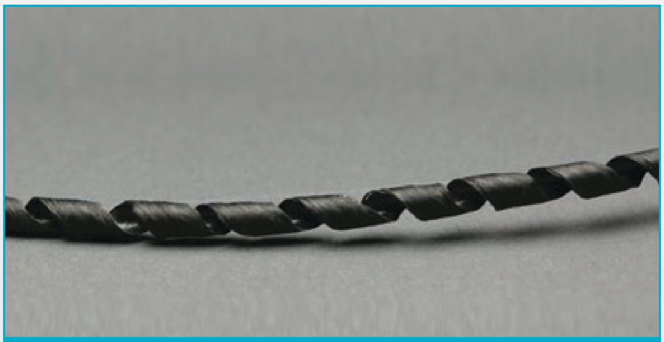

Photo 7

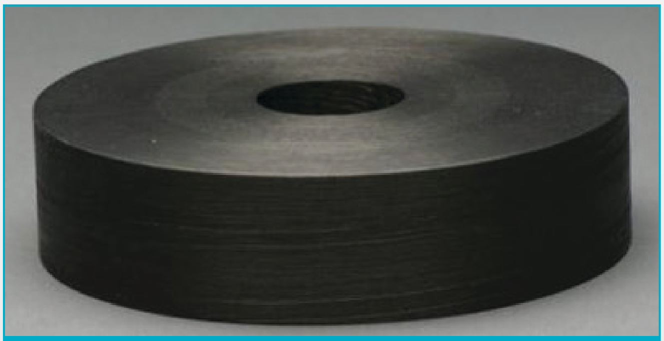

Photo 8

SUMMARY

The advantages of thermoplastic composites are well understood and the applications that use TPCs continue to grow. The ideal manufacturing approach for composites would be a high performance additive manufacturing process that requires no post processes. In-situ consolidated TPC AFP achieves this goal. TPC AFP has been used in serial production for over 20 years and is experiencing exponential growth. Recent literature which casts doubt on the viability of TPC AFP is based on an incomplete model and inaccurate data. Recent advances are further improving the process throughput and efficiency of the process. TPC AFP has a long history of serial production, applications continue to grow and recent advances will facilitate expansion into new markets.

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Acknowledgements: Laser heating for in-situ TPC AFP was developed with support From NYSERDA (New York State Energy Research Development Authority).

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