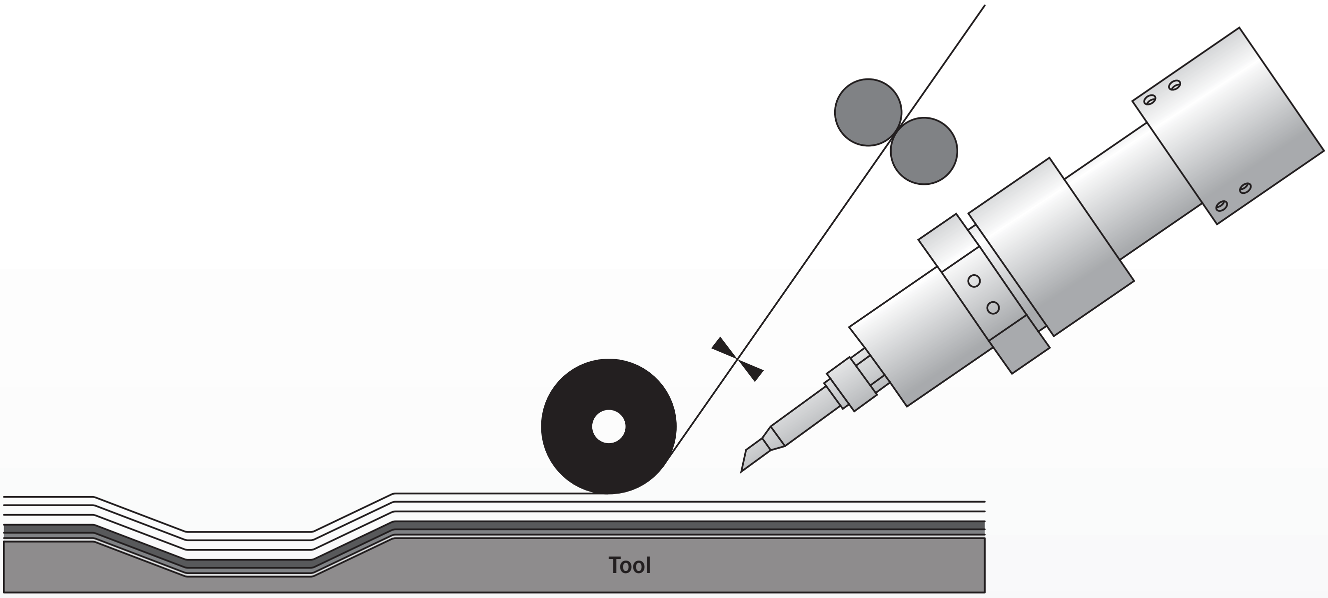
Thermoplastic Composite Aerospace Structures

IN-SITU AUTOMATED FIBER PLACEMENT FOR COST AND WEIGHT SAVINGS



1. INTRODUCTION

In-situ Consolidated Thermoplastic Composite Aerospace Structures

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Automated fiber placement of thermoplastic composite tapes using in-situ consolidation is a well established process for numerous industrial applications. Advances in the process, equipment, materials and fabrication methods coupled with several aerospace development programs indicate that significant cost and weight savings are possible with this out-of-autoclave process. These advances will be presented and key process and material parameters will be discussed. Examples of aerospace structures designed and fabricated using this process will be presented.

2. AUTOMATED FIBER PLACEMENT BACKGROUND

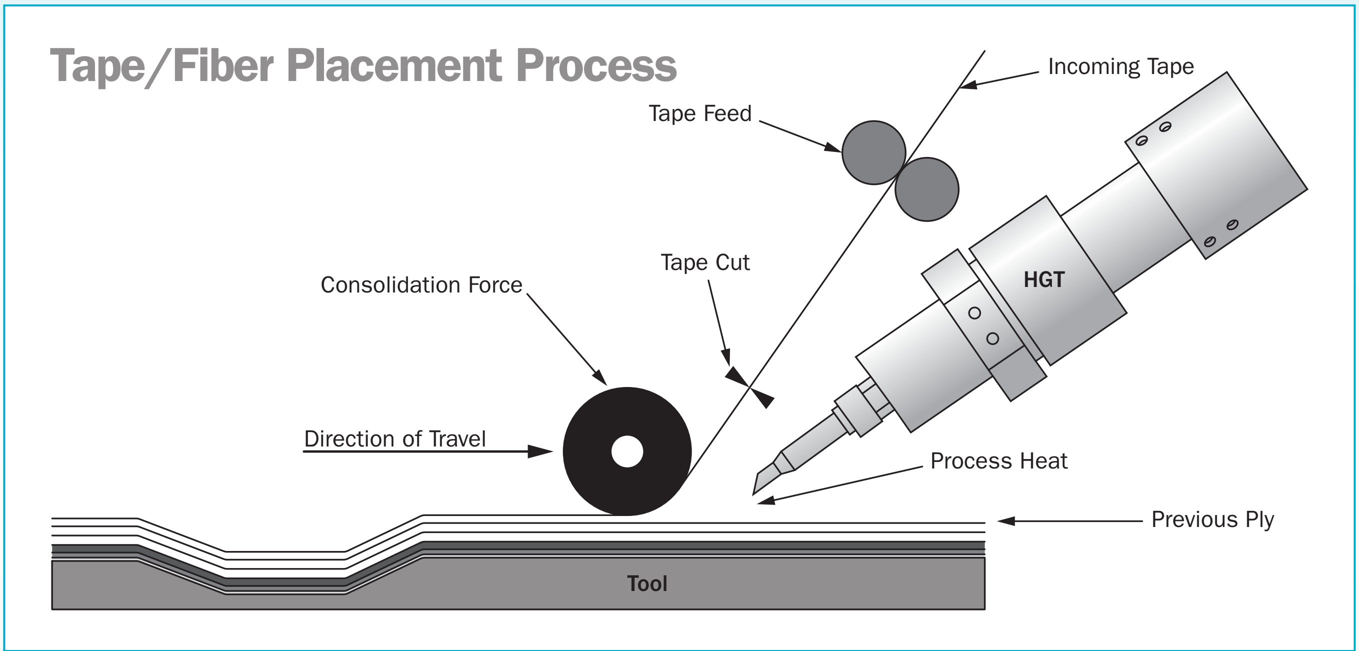

Figure 1: Schematic of AFP process with hot gas heating

Fiber placement was first developed in the early 1980s as an improvement on filament winding. A basic schematic of the Automated Fiber Placement (AFP) process is shown in Figure 1.

The AFP process generally utilizes unidirectional prepreg tape allowing the designer to take maximum advantage of the fiber's strength by precisely positioning the reinforcement along structural load paths. The ability to start or stop a strip anywhere on the surface allows the designer to build plies within complex ply boundaries for pad-ups and complex laminates. Once the mandrel and laminate have been designed in CAD (Computer Aided Design) and optimized with FEA (Finite Element Analysis), a robotic platform then positions the fiber placement head along the mandrel surface to automatically lay-up the composite structure.

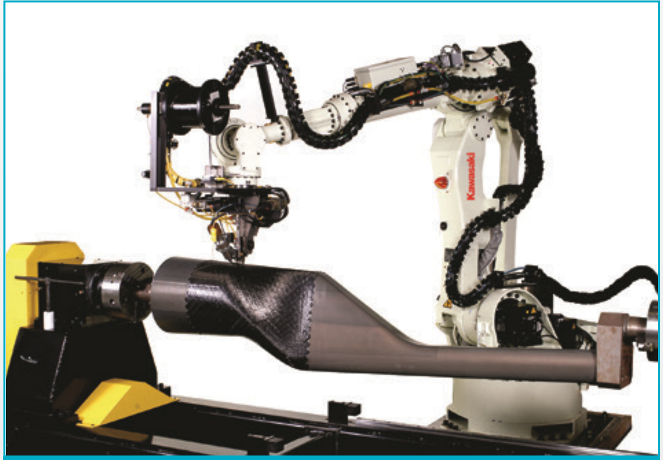

Figure 2: AFP workcell

3. THERMOPLASTIC AFP BACKGROUND

Thermoplastic (TP) matrix composite prepreg tape suitable for aerospace applications was first developed in the early 1980s. The first published papers on TP composite processing models appeared in 1985. Trelleborg Sealing Solutions began development of the TP AFP process in 1986 and shipped the first TP AFP workcell in 1990.

The theory of TP AFP in-situ bonding derives from polymer reptation theory originally suggested by de Gennes. The general concept is that melt bonding of polymer surfaces (including TP composite prepreg) involves three stages – intimate contact, 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. Trelleborg Sealing Solutions uses a heated nitrogen gas stream to apply heat to the bond zone and a compaction roller to apply pressure.

Other heating methods have been tried but the patented Hot Gas Torch (HGT) has proven superior. 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 and a cohesive (TP fusion) bond is achieved.

Semi-crystalline polymers add an additional degree of complexity as the thermal history of TP AFP affects the degree of final crystallinity, which in turn affects chemical resistance, toughness and other properties of the finished laminate.

Additionally, presence of reinforcing fiber, variation in the prepreg tape quality, tool material, part geometry and other factors all add to the complexity of modeling this process. Nevertheless, much prograss has been made over the last decades toward constititive process models.

The process Trelleborg Sealing Solutions employs for TP AFP relies on a small Heat Affected Zone (HAZ) to achieve all three TP fusion bonding stages. This allows for a compact head design providing the ability to fabricate complex structures. An early TP AFP head design is shown in the figure below.

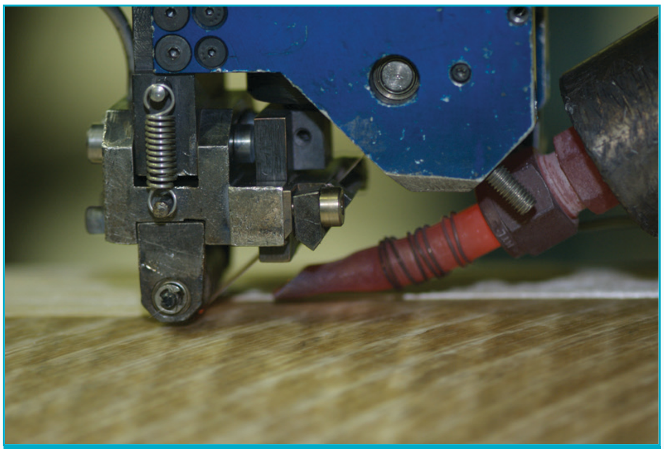

Figure 3: TP AFP process

This relatively small HAZ demands high energy input in order to bring the surfaces up to the desired temperatures quickly while providing 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 lower void content with higher pressure.

The short time the bond zone is maintained under the compaction roller at high throughput rates does not allow as much time for polymer chain diffusion as 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 case of static surfaces in intimate contact.

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 TP AFP.

4. ADVANTAGES OF TP AFP

The use of thermoplastic matrix composite prepreg tape provides many potential benefits over thermoset matrix composite prepreg:

- No refrigeration required – unlimited out-time
- Higher toughness
- Higher service temperature and improved hot/wet performance
- Improved solvent and corrosion resistance
- Recyclable
- Ability to fusion bond (melt bond) with other TP assemblies

In-situ consolidation using TP AFP offers additional advantages:

- Eliminate bagging materials and labor
- Eliminate autoclave costs, floor space, and processing time
- Simpler, longer lasting tooling
- Low residual stress – very thick section parts

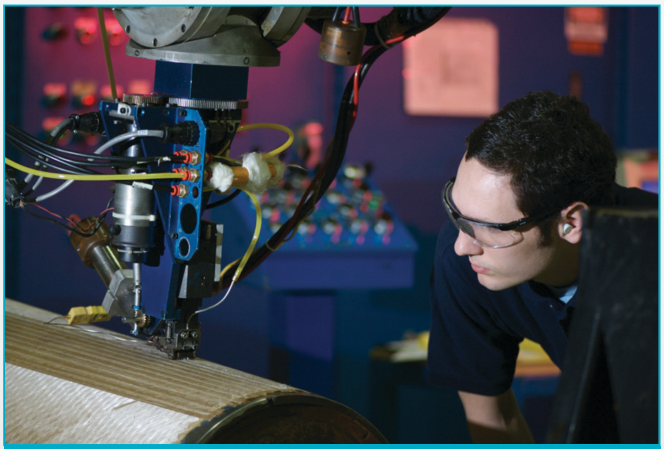

Figure 4 - TP AFP processing

Thermoplastic AFP equipment has several distinct differences as compared to thermoset AFP equipment. Much more heat is needed for thermoplastic fusion bonding since the polymer must be heated above its melt temperature (650 °F or 343 °C in the case of PEEK), not just warmed up (150 °F or 66 °C) to improve tack as for thermosets. Components around the HAZ, such as the compaction roller, must be able to withstand these elevated temperatures. Trelleborg Sealing Solutions uses a patented Hot Gas Torch (HGT) to electrically heat nitrogen for convective heating of the tape and previous ply prior to fusion bonding.

TP Resin	Tg (°C)	Tm (°C)
HDPE	-70	135
PP	110	168
PVDF	-40	171
PA-11	-70	185
ETFE	NA	270
PPS	90	285
PEEK	143	335
PEKK	156	338
PEI	217	amorphous

Table 1 - Thermoplastic resin thermal properties

A list of typical thermoplastic resins used in the TP AFP process is shown in Table 1. Commodity thermoplastics such as HDPE and PP are used where cost is critical and low temperature performance is acceptable.

Engineering thermoplastics such as PEEK, PEKK and PEI can be used at very high temperatures. Virtually any thermoplastic resin can be fiber-placed as long as it can be used to pre-impregnate suitable fiber reinforcement. Graphite reinforced PEEK is the most common thermoplastic prepreg used for AFP aerospace although there is growing interest in other polymers such as PEKK.

PEEK is a semi-crystalline resin which allows it to operate for extended periods above its Tg (glass-transition temperature) in certain applications. Graphite/PEEK parts made with the AFP process are being used in high load applications, where the application temperature approaches 500 °F (260 °C) for up to one year.

5. THERMOPLASTIC AFP APPLICATIONS

The TP AFP process described above has been used at Trelleborg Sealing Solutions for over 20 years to make commercial and industrial components that are currently in use around the world. Current Aerospace applications for thermoplastic AFP involves in-situ bonding of thermoplastic prepreg tape to form a complete structure. Structural elements can likewise be fusion bonded together using this same in-situ process. For example, stringers can be premanufactured and assembled into a tool before the skin is fiber-placed over the stringers.

The cohesive bond formed during fusion bonding of the skin to the stringers avoids problems associated with mechanical fasteners and adhesive bonding.

Figure 5 - AFP structures

Figure 6 - Dassault fusion bonded skin/stringers

A fusion bonded aerospace vehicle skin/stringer assembly can be less expensive to manufacture and lighter than a similar structure with stringers that have been adhesively bonded or mechanically attached with secondary operations. Figure 6 shows a Dassault AFP skin panel with fusion bonded stringers.

Figure 7 - Blackhawk helicopter

Another example of a fusion bonded structure is the integrally bonded helicopter lower tub structure. The lower tub is the floor of the Blackhawk helicopter shown in the figure above. The lower tub structure is fabricated in a similar manner to that shown in Figure 6. The graphite/PEEK I-beams are made by first fiber placing graphite/PEEK box beams which are then cut in half and fusion bonded back-to-back to form I-beams. The I-beams are then assembled into an aluminum tool and the skin is fiber-placed over the top.

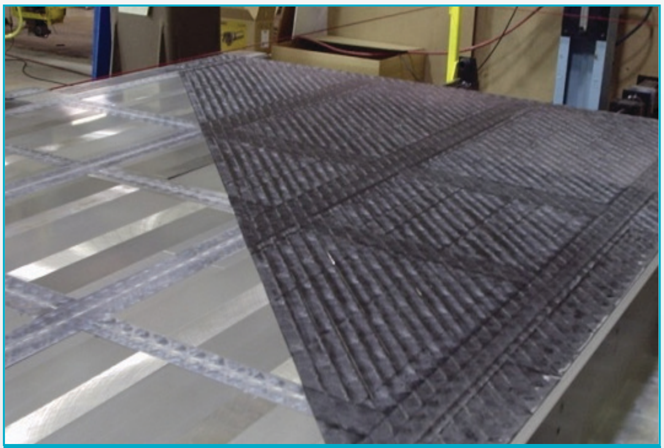

Figure 8 - Integrally bonded tub structure during fiber placement

Again, the TP AFP process fusion bonds the skins to the stringers without secondary adhesives or fasteners.

After the fiber placement of the top skin is complete, the tool is inverted and the spar caps are fiber-placed (which are also integrally bonded). The tool is removed (in segments), the edges are trimmed and a complete integrally bonded graphite/PEEK structure results.

Figure 9: Fusion bonded helicopter tub structure

Advantages of this approach using TP AFP include the following:

- No autoclave (including elimination of bagging costs)
- Almost complete elimination of fasteners
- Weight reduction (25%)
- Manufacturing labor reduction (40%)
- Development labor reduction (40%)
- Tooling cost reduction (initial cost and life-cycle)

SUMMARY

Automated fiber placement of thermoplastic composites is a well established process that has been used for many years for demanding industrial applications. Process modeling, process development, fiber placement equipment and applications development have made great strides in the last decades.

Thermoplastic fiber placement has demonstrated cost reduction, weight reduction and tooling cost reduction in aerospace applications. Although it takes time for new technologies to gain acceptance, the time has arrived for TP AFP.

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