TECHNICAL PAPER

VICTREX AE™ 250 UDT – UNIQUE PAEK PREPREG ALLOWS FAST & EFFICIENT COMPOSITE PARTS MANUFACTURE

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ABSTRACT

With the aim of helping aircraft OEMs and tier suppliers create composite parts faster and more economically, Coriolis Composites and Victrex teamed up to design an Automated Fibre Placement (AFP) process to unlock the potential of VICTREX AE™ 250 UDT. The results showed a significant increase in lay-up speed was possible whilst achieving industry acceptable levels of porosity (<2%) for in-situ consolidation. OoA consolidation showed the potential to reduce the cycle time and energy consumption.

INTRODUCTION

The increasing interest in thermoplastic composites within aerospace is being driven in part by the attraction of fast processing of thermoplastics compared with thermosets, for example using automated lay-up followed by hot stamping, or out of autoclave processing using an oven and vacuum bag to fully consolidate the thermoplastic laminate. A key advantage with thermoplastics over thermosets is that all the polymer chemistry has been completed by the polymer manufacturer prior to leaving the chemical plant- there is no further cross-linking to be done and processing requires only heat, pressure and a little time in order to achieve consolidation. There is no chemical exotherm to manage and there is no risk of achieving only partial cross-linking, nor are there any concerns about cold storage, or material exceeding its shelf-life. However, not all thermoplastics are the same, even within the specific class of high temperature, high performance polyaryletherketone polymers of which PEKK, PEEK and a relative newcomer, VICTREX AE™ 250 belong. This latter polymer has been formulated by Victrex to have the same chemical resistance and high temperature performance as VICTREX™ PEEK (on which it is based) such as Tg but has a lower melting temperature (303 °C vs 343 °C for VICTREX PEEK), which significantly widens its processing window. In trials using VICTREX AE 250 in a joint project between Victrex and Coriolis Composites, a manufacturer of automated fibre placement equipment, the material processed at laydown speeds significantly faster than another polyaryetherketone polymer of the same general type intended for similar applications, partly because of the lower melting temperature. This has significant implications for manufacturers of thermoplastic composite aerospace parts, since manufacturing-time is of the essence for high volume serial production.

VICTREX AE 250 POLYMER AND UNIDIRECTIONAL TAPE

VICTREX AE 250 is a semi-crystalline polymer (25-30 % typically) with a melting temperature some 40 °C lower than PEEK, whilst retaining much of the mechanical, physical and chemical resistance properties typical of PEEK. It falls into the general class of thermoplastic materials called poly aromatic ether ketone polymers (PAEKs). The crystallinity levels are important in order to maintain excellent chemical resistance and must be preserved in processed laminate parts made from VICTREX AE 250 polymer. The fast crystallisation of VICTREX AE 250 compared with some other PAEKs allows this to be achieved except if the laid-up material cools too rapidly, in which case a secondary process may be required to either anneal the part, or re-melt the part allowing it to cool at a rate commensurate with achieving the highest levels of crystallisation. The wider processing window for this polymer allows improved press consolidation and forming.

VICTREX AE™ 250 unidirectional tape ©Victrex

Unidirectional carbon fibre reinforced tapes were utilised in this study, comprising carbon fibres at a volume fraction of 58% and fibre areal weight (FAW) of 192 g/m2. VICTREX AE 250 polymer matrix was impregnated at a mass fraction of 34%.

Slit tapes were utilised by Coriolis Composites at a slit width of 6.35mm and width tolerance of ±0.127 mm for their C1 AFP machine and 38.1 mm ±0.127mm for the CSolo machine. The tapes comprised well-impregnated fibers with minimal voids, which consequently enabled substantially void-free laminates to be manufactured.

AUTOMATED FIBRE PLACEMENT (AFP)

The AFP process utilises a robotic arm to precisely control and accurately lay down strips of composite prepreg tape across the work space on the surface of a shaped tool that defines the geometry of the part. The process utilises rolls of composite prepreg tapes of specific widths pre-cut to tight tolerances. Multiple tapes are laid simultaneously side-by-side under the pressure of a compliant roller with a heat source, often a laser, applied to the carbon fibres between plies and transferred to the polymer that melts just prior to consolidation. The speed at which the tapes can be laid is determined by several factors, including the power delivered by the heat source, but more significantly by the melting and flow characteristics of the polymer matrix. The lower melting temperature of VICTREX AE 250 polymer and its flow characteristics in the melt phase enhance its AFP processability.

In this work the tool was a simple flat plate and the parts were simple flat panels. In some cases, the tool was heated to 140 °C and in other cases the tool was at ambient (approximately 20 °C) temperature.

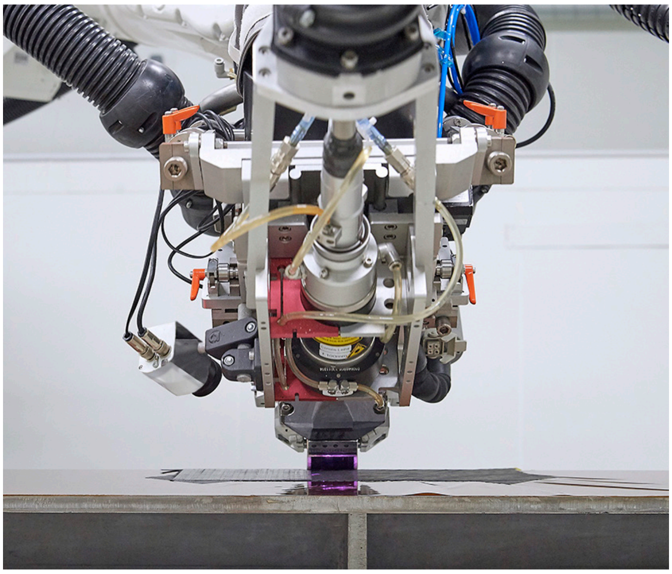
Two process options were explored in the workplan:

1. In-situ consolidation.
2. Post consolidation by Out-of-Autoclave (OoA) processing.

IN-SITU CONSOLIDATION

A Coriolis Composites C1 AFP machine comprising a 6kW laser heat source and compact head with remote creel was used, operating within an AFP work cell at Coriolis Composites plant. It was set up with 8 x 6.35 mm tapes and utilised a compliant roller usually used when making complex shaped parts to demonstrate that this roller is compatible with the VICTREX AE 250 tape and AFP process.

The tool was heated to 140 °C for most cases. Laminates were built under the different conditions detailed in Tables 1 and 2 as 16 ply quasi-isotropic panels.



Coriolis C1 AFP robot ©Coriolis Composites

Table 1 illustrates the results obtained when the lay-up speed was kept at a constant 3 m/min, whilst the other parameters were varied as shown. In these and other tests reported here, the performance of VICTREX AE 250 composite tape was compared with a 'reference' PAEK UDT commonly used for a similar aerospace application. The resulting panels made using VICTREX AE 250 tape were all substantially fully consolidated with zero porosity (established using density measurements) per ISO1183 standard whereas the reference material contained significant (4.6%) porosity which is above the acceptable limits for aerospace applications (2%). In addition, the reference material required more laser power (2.1kW vs 1.6kW) and higher lay-up temperatures (450 °C vs 380 °C) compared with the subject material. Higher lay-up temperatures can lead to higher residual stresses upon cooling and consequential warping of the part.

The results obtained at higher lay-down speeds are illustrated in Table 2. Here the tool was heated in all cases at a temperature of 140 °C. The highest laydown speed possible using the Coriolis Composites C1 AFP machine was 20 m/min and at this speed the VICTREX AE 250 based panel was of good quality with porosity levels around 1.9% which is below the accepted standard of 2% porosity. 20m/min is 6.5x faster than that achieved with the reference material which additionally contained more porosity than the VICTREX AE 250 panels, even at the slow laydown speeds.

Panel #	Description	Head Velocity (mm/s)	Head Velocity (m/min)	Tool Temp. (°C)	Layup Temp. (°C)	Average Laser Power (Watt)	Porosity After OoA (%)
3	Tool at RT	50	3	RT	380	1700	~0
4	Reference	50	3	140	390	1800	0,17 ± 0,07
5	Low Layup Temperature	50	3	140	**345**	**1600**	**0,53 ± 0,05**
A	*Material reference*	*50*	*3*	*140*	***450***	***2100***	***4,6***

Table 1. In-situ consolidation of VICTREX AE™ 250 unidirectional tape at constant speed (3 m/min)

Panel #	Description	Head Velocity		Tool Temp. (°C)	Layup Temp. (°C)	Average Laser Power (Watt)	Porosity After OoA (%)
		(mm/s)	(m/min)				
6	Speed x2	100	6	140	395	2450	0,20 ± 0,08
10	Speed x3,3	166	10	140	400	3200	1,04 ± 0,15
7	Speed x4	200	12	140	405	3700	0,87 ± 0,24
9	Speed x5	250	15	140	410	4300	1,09 ± 0,12
11	Highest Speed	333	**20**	140	420	5000	**1,70 ± 0,20**
A	*Reference Material*	*50*	***3***	*140*	*450*	*2100*	***4,6***

Table 2. In-situ consolidation of VICTREX AE™ 250 unidirectional tape at increasing speeds (6-20 m/min)

Unidirectional carbon fibre reinforced tapes were utilised in this study, comprising carbon fibres at a volume fraction of 58% and fibre areal weight (FAW) of 192 g/m2. VICTREX AE 250 polymer matrix was impregnated at a mass fraction of 34%.

Slit tapes were utilised by Coriolis Composites at a slit width of 6.35mm and width tolerance of ±0.127 mm for their C1 AFP machine and 38.1 mm ±0.127mm for the CSolo machine. The tapes comprised well-impregnated fibers with minimal voids, which consequently enabled substantially void-free laminates to be manufactured.

CRYSTALLINITY (IN-SITU PROCESSING)

An important material characteristic which influences overall mechanical performance is the degree to which the material crystallises through the manufacturing process. VICTREX AE 250 polymer reaches a suitably crystalline state upon cooling from the melt at rates approaching up to 50 °C/minute, with the maximum level of crystallinity being typically in the range 25-30%. Faster cooling reduces the ability to fully crystallise at the point of laminate manufacture and secondary heating above the glass transition temperature must take place if maximum levels of crystallinity are to be achieved in the final part. This can come from a post-AFP annealing step of the whole manufactured part or this can happen during AFP as the laser can heat up above Tg the layers underneath the deposited one. Conversely, Victrex has found that under certain conditions in which the lay-up temperature is set to about 420 °C it is possible to achieve full crystallinity in-situ. Victrex believes that this arises from residual heat in the deposited layer and from subsequent passes of the laser as layers are built one upon the other. This opens the possibility of achieving relatively fast lay-up speeds (~20 m/minute) with low porosity (below 2%) and high crystallinity (>25%) for an in-situ process on heated tooling. Victrex believes that there are further process optimisation opportunities available that will maximise productivity and reduce manufacturing costs.

To conclude, increasing the layup velocity by 6,5 times could generate significant cost saving that could be difficult to be achieved with conventional UDT processed at limited speed. On a generic fairing part, cost savings are anticipated mostly due to productivity increase leading to reduction in capital investment.

OUT OF AUTOCLAVE POST PROCESSING

Whilst in-situ lay-up is an attractive proposition, the use of heated tooling in certain circumstances may be impractical. In these cases, it might be beneficial from a manufacturing throughput standpoint to lay-up faster and later optimise crystallinity, porosity and mechanical properties using a post processing step.

The Victrex and Coriolis trial shows that VICTREX AE 250 polymer based prepreg tape can be laid-up at high speed (at least 60 m/minute) using a Coriolis CSolo AFP machine on room temperature tooling, giving laminates with zero porosity when consolidated in an oven under a vacuum bag to apply 1 bar (100 kPa) consolidation pressure. Table 3 illustrates the lay-up conditions used.

Oven consolidation in this manner requires the part to be held on suitable tooling and for the material to pass through the melt phase (typically heated to 350-380 °C) at which it is held for a period of time to achieve melting throughout the thickness of the laminate (typically 15-30 minutes for thin laminates of below 5mm thickness) and then cooled at a rate usually governed by the cooling ability of the oven. Such a process 're-sets' the polymer condition such that any processing history resulting from the AFP process is erased, stresses are relieved and maximum consolidation is achieved. The mechanical properties of panels made from VICTREX AE 250 polymer based composite tapes, consolidated in an oven under just 100 kPa, can be shown to match those from the same material processed in a consolidation press at some 6x higher pressure (600kPa), as in Table 4.

Panel #	Description	Head Velocity		Tool Temp. (°C)	Layup Temp. (°C)	Average Laser Power (Watt)	Porosity After OoA (%)
		(m/s)	(m/min)				
13	VICTREX AE 250 High Speed	0,8	48	RT	345	3 400	~0
12	VICTREX AE 250 High Speed	**1,0**	**60**	RT	345	3 600	~0

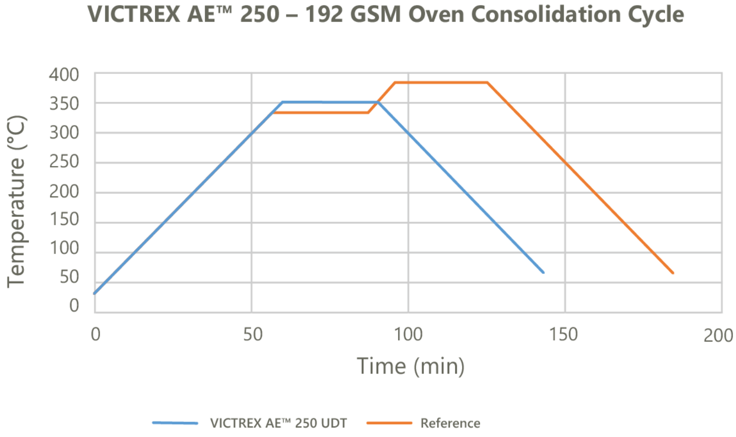
Table 3. Post consolidation of VICTREX AE™ 250 unidirectional tape laid-up at increasing speeds (48-60 m/min)

Properties		Oven Consolidated Compared with Press	
		R.T.	70 °C Wet
In Plane Shear Strength and Modulus	Strength	95%	-
	Modulus	104%	-
Compression After Impact (CAI)		103%	
Mode I (G_{1c}) Fracture Toughness		83%	
Plain Tensile Strength and Modulus	Strength	100%	-
	Modulus	104%	-
Filled Hole Tensile Strength (FHT)		103%	-
Plain Compression Strength and Modulus	Strength	98%	101%
	Modulus	105%	103%
Open Hole Compression (OHC)		102%	-
Filled Hole Compression (FHC)		103%	93%
Bearing Strength		102%	-

Table 4. Mechanical properties comparison between oven consolidated VICTREX AE™ 250 composite laminates and press consolidated laminates against which the data have been normalised.

Our work shows that a consolidation cycle with VICTREX AE 250 is 20% shorter than another PAEK based UDT. This reduction in cycle time may be converted to cost savings for manufacturing aerospace composite parts.

The resulting laminates following AFP lay-up and OoA processing display excellent consolidation and freedom from voids/porosity and even show sufficient polymer flow to fill the spaces often associated with the edges of ply drops (circled in Figure 1). The white circle illustrates the area of polymer flow at a ply-drop. These results are in accordance with CScans performed on the entire panels and showing no delamination nor volumetric porosities whatsoever.



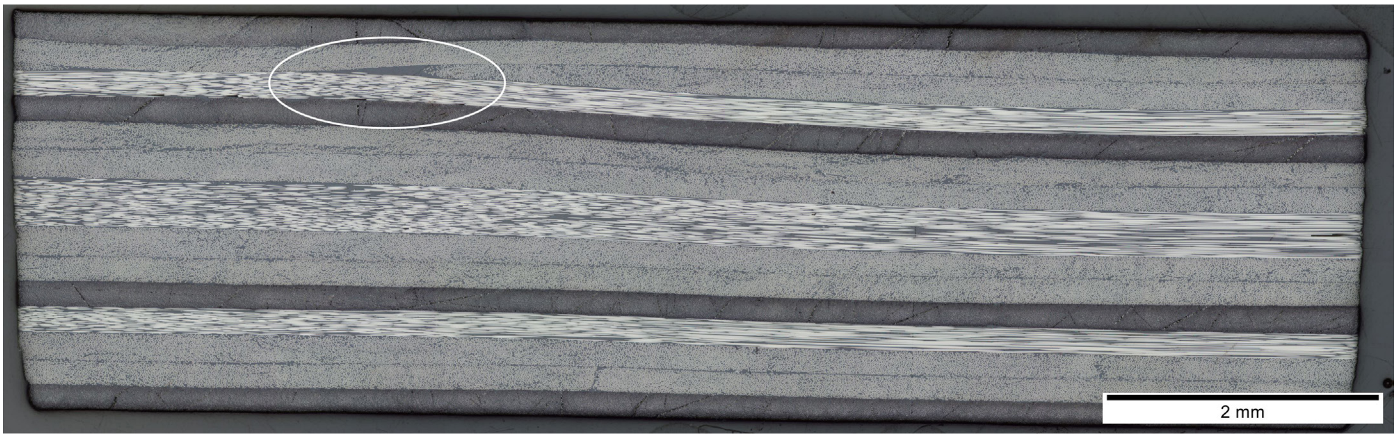


Figure 1. Polished optical microsection through an oven consolidated laminate made from VICTREX AE 250 composite tape laid up on a Coriolis C-Solo machine at 60 m/min

CONCLUSION

In-situ consolidation can run at 6.5x faster than another similar polymer intended for a similar application and with high tool temperatures (in excess of 140 °C) and high lay-up temperatures it is possible to achieve acceptable levels of crystallinity although the mechanical properties may be compromised with interlaminar shear strength being some 50-60% of the pressed panel standard. Generally, VICTREX AE 250 polymer requires less laser power and can be laid-up at lower temperatures than other similar materials because of its lower melting temperature. These factors can lead to energy savings and or the specification of lower power lasers.

For OoA consolidation, the low melting temperature and easy flow characteristics of VICTREX AE 250 polymer enable fast lay-up by automated fibre placement of pre-preg tapes at speeds equal to, or exceeding, 60 m/minute on ambient temperature tooling if post processing in an oven is allowed. This is some 2.5x faster than another high engineering polymer of the same class intended for the same application. Oven consolidation post AFP produces fully consolidated laminates with very low (~zero) porosity with excellent mechanical properties that match those achieved with press consolidation.

The results of this work are significant in terms of speed and efficiency for PAEK thermoplastic composite materials processed via AFP and OoA. These advantages are a potential step change for the manufacture of thermoplastic composites parts made from AFP and OoA processes. A first estimation of the floor-to floor ratio leads to a ratio of 400 kg/hour tape laydown when using a 20 tows machine with 1.5" wide 192GSM tape.

Additional process optimisation work is planned, as Victrex aims to further demonstrate the processing benefits of VICTREX AE 250 based composites for the aerospace industry.

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