INFLUENCE OF LAYUP SPEED ON THE QUALITY OF THERMOPLASTIC PREFORMS MANUFACTURED BY LASER-ASSISTED AUTOMATED FIBRE PLACEMENT

Mattia Di Francesco[1], Mario A. Valverde[2], Carwyn Ward[2], Peter F. Giddings[1], Giuseppe Dell'Anno[1], Kevin Potter[2]

[1]National Composites Centre, Bristol & Bath Science Park, Emersons Green, Bristol BS16 7FS, UK
Web Page: www.nccuk.com
Email: Mattia.DiFrancesco@nccuk.com, Peter.Giddings@nccuk.com, Giuseppe.Dellanno@nccuk.com
[2]ACCIS, University Walk, Univeristy of Bristol, Bristol, BS8 1TH, UK,
Web Page: www.bristol.ac.uk
Email: mv12733@my.bristol.ac.uk, C.Ward@bristol.ac.uk, K.Potter@bristol.ac.uk

Keywords: Automate fibre placement (AFP), Process characterization, Thermoplastic, CF/PEEK

Abstract
Laser-assisted Automated Fibre Placement of carbon fibre reinforced PEEK at the maximum machine layup rate of 1000 mm/s requires the machine to accelerate and decelerate during the layup. However, changing the speed while constantly controlling the laser power to maintain the nip-point temperature constant can affect the thermal history of the material during its processing. This work sought to identify the influence of the deposition speed on the laminate's microstructure and interply shear strength, and shows that for the same nip-point temperature the crystallinity of the preform reduces as the deposition speed increases. It was found that the interply shear strength reduces significantly at a deposition speed of 800 mm/s, while no change was observed between 200 and 400 mm/s. It is therefore shown that a high and variable layup speed is incompatible with the goal of an in-situ consolidated CF/PEEK laminate, having properties comparable to an autoclave consolidated one, but that currently available material and equipment can be used to layup a preform at high rate for consolidation in a secondary subsequent manufacturing process.

1. Introduction

Automated Fibre Placement (AFP) is an established composite manufacturing technology used for the deposition of carbon fibre reinforced high-performance thermoplastic materials [1]. A suitably controlled laser heater is used to melt the thermoplastic matrix as it reaches the deposition site, typically targeting temperatures of up to 400 °C [2].

The laser-assisted AFP process can be characterised in terms of the measured temperature at the convergence between the layup roller and the substrate, namely the nip point [3]. However, the thermally affected zone extends beyond the nip point and the full thermal history, not simply the nip-point temperature, determines the micro and meso structure of the material and, ultimately, its mechanical properties [4]. This is influenced also by other factors, such as the deposition speed, the compaction pressure and the material's thermal properties [5].

The objective of this work is to identify the influence of the deposition speed and nip point temperature on the laminate's microstructure (crystallinity) and mechanical properties (interply shear strength).

Excerpt from ISBN 978-3-00-053387-7

2. Experimental setup

2.1. Machine details, dimensions and setup design

An Automated Fibre Placement machine by Coriolis Composites SAS (Figure 1a) was used to deposit simultaneously eight 6.35 mm wide Cytec Industries Inc. APC-2/AS4 145/34 carbon fibre Poly Ether Ether Ketone (PEEK) tapes (Table 1) over a 150 µm thick PEEK film (Victrex® APTIV® 1000) vacuumed to the surface of an aluminium tool to produce 8 plies thick, 50.8 mm wide and 650 mm long unidirectional (UD) strips. Two pairs of 25.4 mm wide 25 µm thick polyimide tape were introduced between the 4th and 5th ply (laminate's midplane) along the width of each strip to isolate a 6 mm long area. The heat source for the process was a Laserline GmbH LDF 6000-100 6 kW fibre-coupled diode laser (two diode stacks at $\lambda = 975 \pm 10$ nm and two at $\lambda = 1025 \pm 10$ nm). The laser is installed remotely from the fibre placement head and the beam is guided through a fibre optic cable to a homogeniser optic to deliver a nominally homogeneous (≈ 7 % power variation across the course width), 57 mm wide and 28 mm high rectangular laser beam at the focal point (Figure 1b). The laser power was adjusted to achieve the target visible nip-point temperature for each combination of speed and temperature as outlined in Table 2.

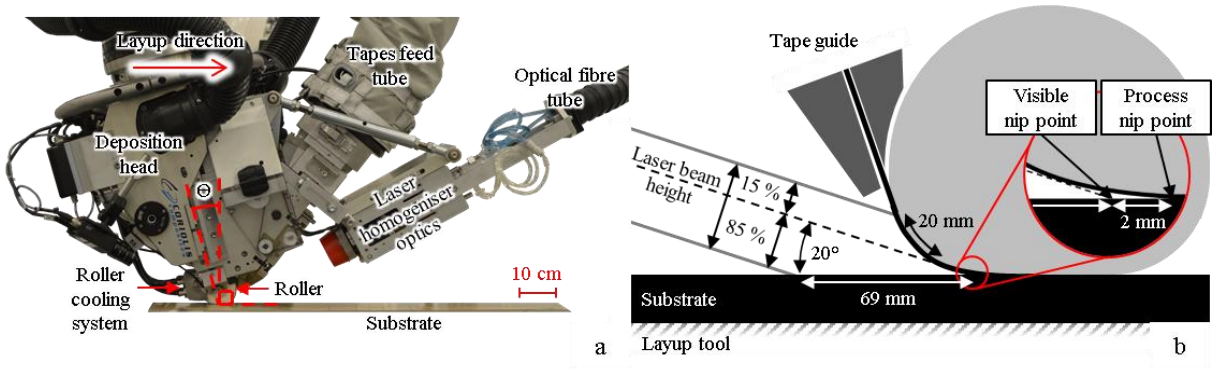

Figure 1. Laser-assisted Coriolis Composites Automated Fibre Placement (AFP) machine head showing the installation of the laser homogeniser optics (a) and laser beam target, power split and temperature measurement location (b).

Table 1. Characteristics of the as-supplied Cytec APC-2/AS4 145/34 [4].

Property	Value (95% confidence interval)
Surface roughness (R_a)	4.10 ±0.34 µm
Thickness	151.8 ± 24.2 µm
Fibre volume fraction	56.7 ± 14.6 %
Void content	1.3 ± 1.8 %
Glass transition temperature (midpoint)	141.4 ± 2.8 °C
Melting temperature	328.1 ± 2.3 °C (onset) 344.9 ± 1.9 °C (peak)

Excerpt from ISBN 978-3-00-053387-7

Table 2. Manufacturing configurations.

Deposition speed, mm/s	Target nip-point temperature and set laser power, W		
	340 °C	380 °C	400 °C
200	2328	-	3036
400	3637	4261	4886
800	5755	-	-*

*the maximum laser power does not allow achieving a nip-point temperature of 400 °C at 800 mm/s

Other machine configuration parameters which can be adjusted and which affect the temperature distribution in the process, but were kept constant for the purpose of this work are: the head tilt (Θ = - 7°, Figure 1a), the roller design (70 mm diameter) and material (40 Shore hardness silicone), the compaction force (1025 ±3 N at 95 % confidence interval) and the air pressure of the forced convection roller cooling system (6 bar).

2.3. Temperature measurement setup

The material surface temperature in the nip point region was measured using a FLIR A325 Long Wave Infrared (LWIR) (λ = 7.5-13 μm) thermal camera. The camera's infrared detector has a resolution of 320 x 240 pixels (≈ 0.5 mm/pixel). All recordings were made at 60 Hz.

The apparent emissivity of the material when imaged at an angle of 20° in the 350 to 450 °C temperature range was determined in accordance with the ASTM E1933 standard by comparing the temperature measured by the thermal camera with that measured by a thermocouple placed to be in intimate contact with the material surface. The apparent emissivity is 0.80. Other relevant parameters which affect the thermal camera temperature reading are the distance from the target (0.3 m) and the environmental conditions: ambient temperature (20 °C) and relative humidity (40 %).

The thermal camera was used to measure the substrate's surface temperature up to the visible nip point (Figure 1b). The temperature in the bulk of the material was measured using a 25 μm diameter K-type thermocouple placed at the interface between the 4th and 5th ply in the middle of each strip. The thermocouple's output was logged at 90 Hz. The data collected by the thermal camera together with those collected by thermocouples allowed characterising the full thermal history of one location of the laminate.

2.4. Microstructure characterisation

The crystallinity content of the matrix in the as-supplied and the as deposited state was determined in accordance with the ASTM D3418-12 standard by Differential Scanning Calorimetry at a heating rate of 10 °C/min and assuming the heat of fusion for the 100 % crystalline PEEK to be 130 J/g [6].

2.5. Mechanical properties

The samples were prepared in accordance with the procedure presented by [7]. The portion of each strip containing the polyimide tapes was slit into eight lap shear samples, one per tape. The nominal gauge length, width and overlap of the samples were 200, 4 and 6 mm respectively. Through thickness cuts were made above the polyimide tape on opposing side of the samples (Figure 2).

The samples were tested at room temperature on a Shimadzu testing machine following a protocol based on the ASTM D5868 using a 10 kN rated load cell and a 13 mm/min loading rate. The apparent lap shear strength of the inter tape interface was computed by dividing the peak load by the effective lap shear area of the failed samples measured using a high resolution scanner (600 dpi, 42 μm/pixel).

Excerpt from ISBN 978-3-00-053387-7

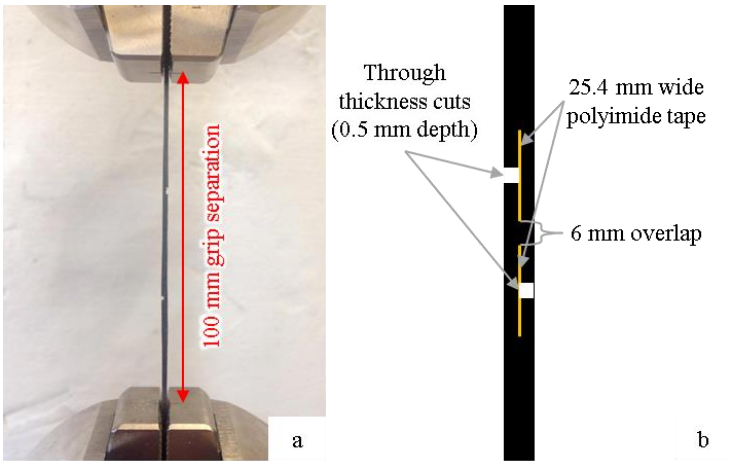

Figure 2. Lap shear specimen loaded in tensile machine showing the grip separation (a) and sample's schematic showing the polyimide tape used to isolate the 6 mm long overlap (b).

3. Experimental results

3.1. Experimentally determined thermal history

The thermal history of the interface between the 4th and 5th ply of the UD strips during deposition of the 5th to the 8th ply is reported in Figure 3 (200 mm/s) amd Figure 4 (400 mm/s); together with the measured glass transition temperature (T_g, see Table 1), the onset melt temperature (T_{om}, see Table 1) and the crystallization range (T_c [8]). The temperature history was truncated below the T_g on cooling for the sake of clarity of the charts. No data was collected for the 800 mm/s case because the thermocouple was damaged during layup and unable to record.

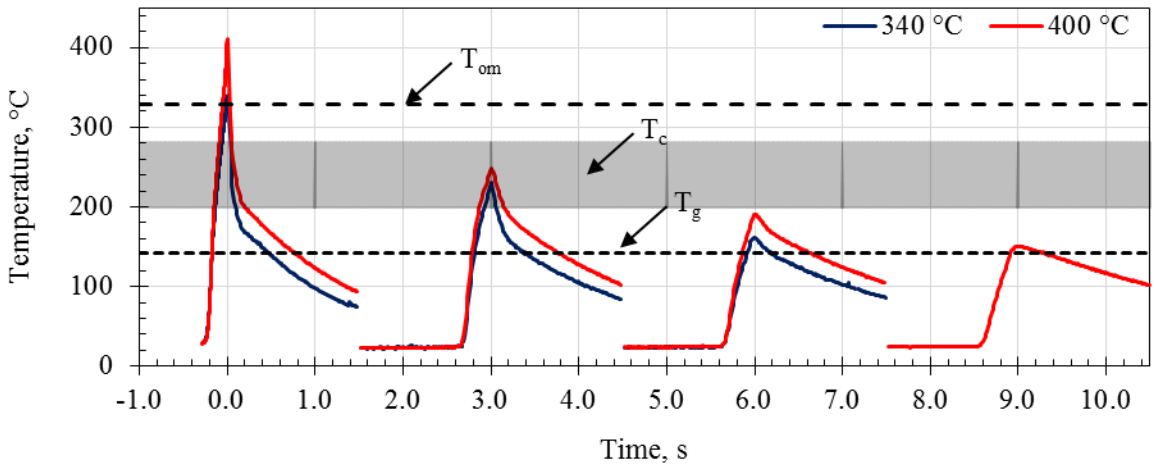

Figure 3. Temperature history of the interface between the 4th and 5th ply of the UD strips during deposition of the 5th to the 8th ply, together with the glass transition temperature (T_g), the onset melt temperature (T_{om}) and the crystallisation temperature range (T_c) at a deposition speed of 200 mm/s.

Excerpt from ISBN 978-3-00-053387-7

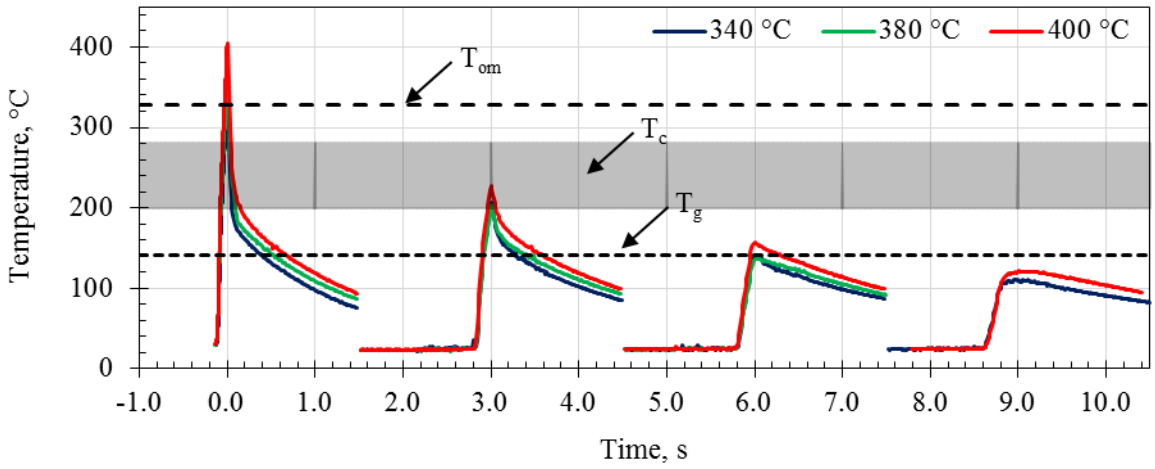

Figure 4. Temperature history of the interface between the 4th and 5th ply of the UD strips during deposition of the 5th to the 8th ply, the glass transition temperature (T_g), the onset melt temperature (T_{om}) and the crystallisation temperature range (T_c) at a deposition speed of 400 mm/s.

Figure 3 and 4 show that the time the material spends in the crystallization range and above the matrix's glass transition temperature is inversely proportional to the layup speed and directly proportional to the nip-point temperature.

3.2. Microstructure

The degree of crystallinity of the as-supplied Cytec APC-2/AS4 145/34 was 13.4 ± 4.0 % (95 % confidence interval). The degree of crystallinity of the processed material is reported in Table 3 and shows that increasing the speed from 200 to 800 mm/s while maintaining the nominal nip-point temperature constant (340 °C) caused a statistically significant 2.9 ± 2.0 % ($p = 0.019$) decrease in crystallinity. Conversely, increasing the nip-point temperature from 340 to 400 °C at constant deposition speed of 200 mm/s caused a statistically significant ($p = 0.014$) 3.0 ± 1.8 % increase in crystallinity. No sample showed a degree of crystallinity close to the equilibrium volume fraction crystallinity of PEEK of 37 % [9].

Table 3. Measured degree of crystallinity for three manufacturing configuration.

Deposition speed, mm/s	Nominal visible nip-point temperature and measured degree of crystallinity (95 % confidence interval)	
	340 °C	400 °C
200	18.8 ± 1.9 %	21.8 ± 3.7 %
800	15.9 ± 0.8 %	-

3.3. Preforms' mechanical properties

The measured apparent interply shear strength for each of the six manufacturing configurations is reported in Figure 5. It shows that increasing the nip-point temperature from 340 to 400 °C at constant deposition speed (200 & 400 mm/s) caused a statistically significant ($p = 0.003$ & $p = 0.000$) 80 % increase of the interply shear strength in both cases. Conversely, increasing the deposition speed from 200 to 400 mm/s at a constant nip-point temperature 340 or 400 °C caused a statistically insignificant change of the interply shear strength ($p = 0.925$ & $p = 0.855$). A further 100 % increase in speed from 400 to 800 mm/s caused the interply shear strength to reduce by 40 % ($p = 0.001$).

Excerpt from ISBN 978-3-00-053387-7

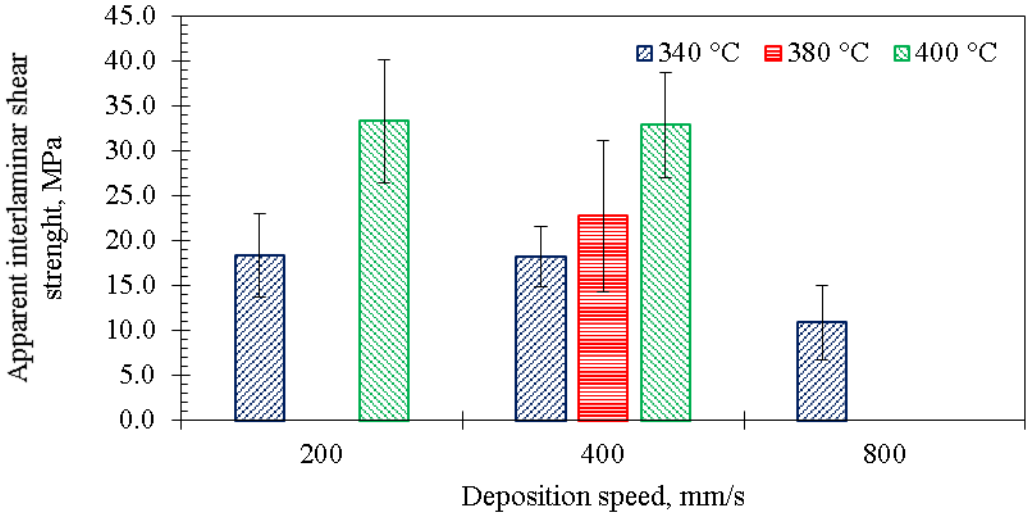

Figure 5. Apparent interply shear strength as a function of the manufacturing parameters (deposition speed and nip-point temperature). The error bars indicate the 95 % confidence interval.

4. Discussion

The measured interply shear strength at 200 mm/s deposition speed (14 to 40 MPa, see Figure 5) is in agreement with the results reported by [7], for similarly designed samples manufactured at the same deposition speed and on a similar laser-assisted AFP machine over a range of compaction forces and laser powers (22 to 40 MPa [10]). But the measured interply shear strength and crystallinity values fall well below the benchmark set by fully consolidated laminates (64 MPa [11] and 37 % [9] respectively) in all cases.

For a given layup speed, increasing the input heater power - i.e. the nip-point temperature - has a positive and significant effect on both the crystallinity of the matrix and the interply shear strength. The onset of significant thermal degradation was not reached in this study, but an upper limit exists as demonstrated by [12], which reported a reduction of interply shear strength above 500 °C at 100 mm/s and 550 °C at 400 mm/s. This limits the extent to which a higher set laser power and nip-point temperature can be used to compensate for the negative impact of increasing the layup speed. For a given target layup quality (crystallinity, mechanical properties, etc.) and manufacturing setup (laser spot size [4], layup tool temperature [13], material [14], etc.) an upper limit to the deposition speed exists.

The target material state for a laminate manufactured in a single step (in-situ) is set by the hand laid and autoclaved laminate benchmark. The target material state of a preform manufactured for subsequent consolidation will depend on the post-processing step. At a first approximation, it is reasonable to assume that a poorly welded preform, similar to a hand laid and ultrasonically spot welded one, is sufficient as an input for autoclave or press consolidation. A partially consolidated preform was shown to produce better laminates than a nearly fully consolidated one when the preform is post processed in an oven under vacuum pressure only [15].

Excerpt from ISBN 978-3-00-053387-7

5. Conclusions

This work aimed to build on the extensive literature base on laser-assisted Automated Fibre Placement of carbon fibre reinforced thermoplastics, by demonstrating that a coherent preform can be manufactured at deposition rates comparable with those conventionally used for carbon fibre reinforced thermosets. This was attempted using commercially available equipment and materials. The outcomes have supported previous evidence that shows the negative impact of increasing the layup speeds on the quality of the weld between the plies, and on the degree of crystallinity in the matrix. Thus it reinforces the fact that the high deposition rate required by industry is incompatible with the goal of an in-situ consolidated laminate having mechanical properties comparable to an autoclaved example whne using currently available materials and machines. An effective and efficient two step process involving AFP layup followed by consolidation in an autoclave, press or oven will be investigated as part of further work to this paper.

Acknowledgments

This work was supported by the Engineering and Physical Sciences Research Council through the EPSRC Centre for Doctoral Training in Composites Manufacture [grant number EP/K50323X/1].

References

[1] Lukaszewicz, D.H. J., Ward, C., Potter, K. D. The engineering aspects of automated prepreg layup: History, present and future. Composites Part B: Engineering, 2012, 43.3: 997-1009.

[2] Di Francesco M., Veldenz L., Koutsomitopoulou A., Dell'Anno G., Potter K. On the development of multi-material automated fibre placement technology. *Proceedings of the International Conference on Manufacturing of Composites ICMAC2016, Bristol, UK,* June 24-25 2015

[3] Stokes-Griffin, C. M., Compston, P. The effect of processing temperature and placement rate on the short beam strength of carbon fibre–PEEK manufactured using a laser tape placement process. Composites Part A: Applied Science and Manufacturing, 2015, 78: 274-283.

[4] Di Francesco M., Giddings P. F., Scott M., Goodman E., Dell'Anno G., Potter K. Influence of laser power density on the meso-structure of thermoplastic composite preforms manufactured by automated fibre placement. *Proceedings of the SAMPE Conference and Exhibition, Long Beach, USA,* June 23-26 2016.

[5] Grouve, W. J. B., Warnet, L. L., Rietman, B., & Akkerman, R. On the weld strength of in situ tape placed reinforcements on weave reinforced structures. Composites Part A: Applied Science and Manufacturing, 2012, 43.9: 1530-1536.

[6] Blundell, D. J., Osborn, B. N. The morphology of poly (aryl-ether-ether-ketone). Polymer, 1983, 24.8: 953-958.

[7] Stokes-Griffin, C. M., Compston, P. Investigation of sub-melt temperature bonding of carbon-fibre/PEEK in an automated laser tape placement process. Composites Part A: Applied Science and Manufacturing, 2016, 84: 17-25.

[8] Tardif, X., Pignon, B., Boyard, N., Schmelzer, J. W., Sobotka, V., Delaunay, D., & Schick, C. Experimental study of crystallization of PolyEtherEtherKetone (PEEK) over a large temperature range using a nano-calorimeter. Polymer Testing, 2014, 36: 10-19.

[9] Velisaris, C. N., Seferis, J. C. Crystallization kinetics of polyetheretherketone (PEEK) matrices. Polymer Engineering & Science, 1986, 26.22: 1574-1581.

Excerpt from ISBN 978-3-00-053387-7

[10] Stokes-Griffin, C. M., Compston, P. Laser-Assisted tape placement of thermoplastic composites: the effect of process parameters on bond strength. Sustainable Automotive Technologies 2013, 133-141.

[11] Yang, F., Pitchumani, R. Healing of thermoplastic polymers at an interface under nonisothermal conditions. Macromolecules, 2002, 35.8: 3213-3224.

[12] Stokes-Griffin, C. M., Compston, P. The effect of processing temperature and placement rate on the short beam strength of carbon fibre–PEEK manufactured using a laser tape placement process. Composites Part A: Applied Science and Manufacturing, 2015, 78: 274-283.

[13] Khan, M. A., Mitschang, P., Schledjewski, R. Parametric study on processing parameters and resulting part quality through thermoplastic tape placement process. Journal of Composite Materials, 2013, 47.4: 485-499.

[14] Lamontia, M. A., Gruber, M. B., Tierney, J. J., Gillespie Jr, J. W., Jensen, B. J., & Cano, R. J. In situ thermoplastic ATP needs flat tapes and tows with few voids. *Proceedings of the SAMPE Europe 30th. International Jubilee Conference and Forum SEICO 09, Paris France*, March 23-25 2009.

[15] Zhang D, Heider D, Gillespie Jr JW. Volatile Removal During Out of Autoclave Processing of High Performance Thermoplastic Composites. *Proceedings of the Composites and Advanced Materials Expo CAMX, Orlando, USA*, Oct 13-16 2014.

Excerpt from ISBN 978-3-00-053387-7