CHALLENGES FOR THERMOPLASTIC-AUTOMATED FIBER PLACEMENT (TP-AFP) WITH IN SITU CONSOLIDATION ON 3D PARTS

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Abstract
Laser assisted Thermoplastic-Automated Fiber Placement (TP-AFP) is of big interest due to its possibility of the laminate’s in situ consolidation during lay-up. On simple geometries like flat plates or cylindrical tubes, the process can be regarded as a steady-state process, as the thermal boundary conditions don’t change during placement. Based on an optimized 2D steady-state process this paper focuses on describing the differences for 3D lay-up on v-shaped tools with a rounded corner. Due to the geometry, the heating behavior changes, which leads to local overheating of the material within the laser spot. Overheating occurs especially on the substrate laminate. Test specimens with different leg angles are manufactured and the heating behavior is logged and described. During placement the corner section gets overheated, while the closed loop control of the machine induces too low temperatures behind the corner. The specimens are mechanically tested for their radial out-of-plane tensile strength in the curved segment based on ASTM 6415. A decreasing failure strength was measured for specimens with sharper leg angles.

1. Introduction

Automated Fiber Placement (AFP) is a well-established manufacturing process for aerospace parts. The high degree of automation reduces expensive manual labor time and guarantees constant high part quality. Thermoset prepregs are used for state-of-the-art aerospace parts produced by AFP. Thermoset processing requires compaction cycles during and a curing cycle in an autoclave after the lay-up. In contrast, using thermoplastic (TP) composite materials for AFP may reduce processing times through in situ consolidation during placement. Thus, time and energy consuming autoclave consolidation including vacuum bagging and very high temperatures above the matrix’ melting temperature over a long period of time can be avoided.

In situ consolidation requires accurate process control during lay-up. Predominant process parameters are the process temperature (respectively heating profile) and the cooling rate to solidify the composite during the compaction by the placement head’s roller. It is aimed for equal temperature of tape and substrate in the joining area (nip point). The absolute process temperature has to be high enough to melt the thermoplastic matrix within the tape lowering its viscosity while its degradation threshold must not be exceeded [1].

For steady-state 2D lay-up processes optimal process parameters have been investigated for different types of TP-AFP machines and tape materials [2–5]. Based on a 2D lay-up setup, this paper investigates the challenges of the material heating by a laser at the nip point during 3D lay-up of sharp convex corners.

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2. TP-AFP Process for In Situ Consolidation

2.1. TP-AFP Machine

A fiber placement machine from AFPT GmbH (Dörth, Germany), derived from their winding technology, is used for placement trials. A conformable silicone consolidation roller with 64 mm in diameter and 30 mm in width is used for compaction. A near infrared diode laser (wavelength 1030 nm – 1060 nm) is used for material heating. An optics forms a rectangular laser spot heating both the incoming tape and the substrate laminate. AFPT's machines have comprehensive data logging, involving process parameters such as tape tension, compaction force, deflection of the compaction roller, max. process temperature, temperature of incoming tape and substrate laminate in reference to the robot's position. These data logged during placement of the test specimens will be evaluated in section 3.3.

2.2. 2D TP-AFP with In Situ Consolidation

Although TP-AFP features high material temperatures and high cooling rates it can be regarded as a steady-state process for certain part geometries, for example when manufacturing flat plates or winding of cylindrical tubes. Up to now research has mainly focused on these simple part geometries with steady-state processes. In this case the heating strategy can be optimized to a fixed set of process parameters as the heating area won't change its size during lay-up. By optimizing the process parameters in situ consolidation was demonstrated [3,6–8].
In recent years, nip point heating strategies were mostly used with high power near infrared (NIR) lasers and a rectangular focal spot height of up to 60 mm. The laser spot on the composite is formed by fixed laser optics and cannot change its shape during lay-up. Heating can start up to 50 mm before the nip point allowing relatively moderate heating rates compared to other TP-AFP heating strategies. This makes the process less sensitive to deviations e.g. caused by tape inhomogeneity or robot trayectory tolerances.

Additionally AFPT machines use a closed loop control for the laser power and laser angle (Figure 1). An infrared thermal camera measures the absolute temperature and temperature distribution in the nip point area and automatically adjustes these parameters. The machine user defines the set-point temperature suitable for the polymer in the tape and the closed loop control adjusts the laser power accordingly. Thus, laser power is adjusted automatically for the respective tape width and thickness.

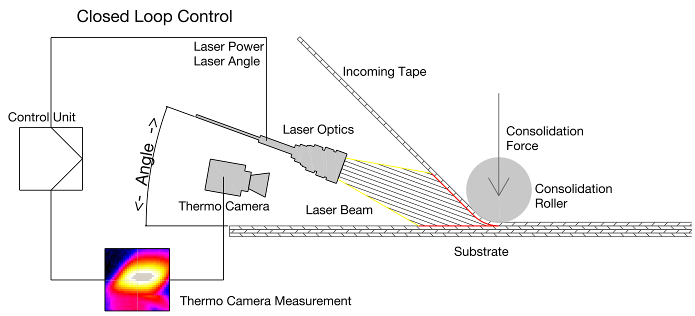

Figure 1. Schematic of AFPT's closed loop control during AFP process

Also, with increasing laminate thickness the laser angle and thus the laser spot distribution, are adjusted as thicker substrates need higher heat input to achieve the same temperature as the single layer incoming tape.
By using optimized lay-up parameters combined with a process temperature closed loop control the required laminate quality according to aerospace standards is achieved for flat laminates [3,9,10].

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2.3. Heat Transfer for 3D Laser TP-AFP

As the laser optics is mounted on the placement head, its position relative to the incoming tape isn't influenced by the lay-up geometry. This also means that the heat input by the laser into the incoming tape doesn't change. Only the part of the laser radiation reflected by the substrate towards the incoming tape will vary compared to steady-state 2D lay-up.

Accurate control of the substrate's heating by the laser is the dominant effect with respect for laminate quality during 3D lay-up. The intensity of the laser heating on the substrate corresponds to the following relationship:

$$I = \frac{P_{Laser}}{A_{illuminated}} \cdot t_{illuminated} \cdot \alpha \tag{1}$$

I = Specific engergy intensity;
P_{Laser} = Power of the laser beam;
$A_{illuminated}$ = Illuminated area by laser spot;
$t_{illuminated}$ = Duration of laser heating of point on the substrate;
α = Absorptivity;

Only the laser power can be adjusted independently from the geometry to be manufactured and has a direct influence on the energy intensity and thus on the material temperature.
The curvature of the part defines the projected area ($A_{illuminated}$) of the laser beam. This can be seen in Figure 2 for 2D lay-up and a following rounded edge (3D lay-up). Due to the curvature the projected length of the laser spot heating the substrate laminate before the nip point changes.

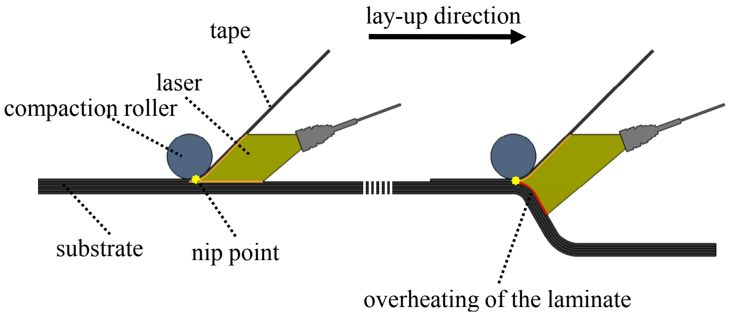

Figure 2. Energy intensity of the laser spot for 2D steady-state (left) and 3D non-steady (right) laser heating

When the AFP head moves around a corner, the illuminated time ($t_{illuminated}$) of the substrate material within the laser spot also varies from the steady-state 2D process. The laser already heats the substrate behind the corner and the laser spot remains on this heated region for a moment while the placement head is turning around the corner (compare Figure 2). This laser spot standstill on the same area of the substrate leads to overheating of the region right behind the corner.

When laying 3D parts, the angle of incidence of the laser spot relative to the substrate laminate changes as well along the change of the geometry's curvature. Figure 3 shows the absorptivity rate of CF/PES (Suprem™ T 55% AS4 / PES-4100) measured using a spectrophotometer with an integrating sphere at 1060 nm. It also shows the increase of absorptivity of about 10 % when the laser's angle of incidence changes from 65° to 90°. This will happen when the nip point has not jet reached the curved corner of the part, but part of the projected laser beam heating the substrate already has. This will add to the increased laser intensity on a curved section. It is assumed that different polymers do not have a decisive influence on the absorptivity, as the laser beam is absorbed by the carbon fibers.

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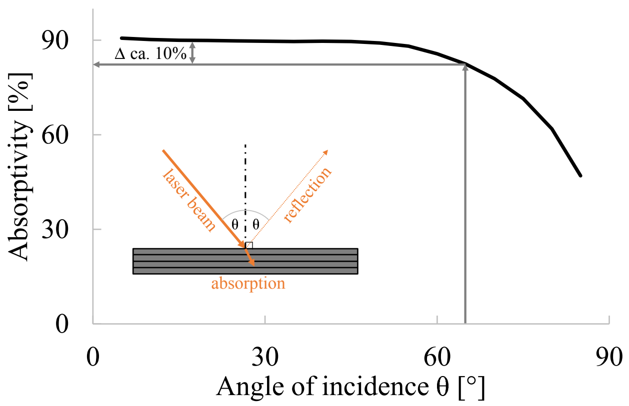

Figure 3. Absorptivity over angle of incident for CF/PES, 55 % FVC, at 1060 nm

Another influencing factor is the lay-up speed of the placement process. However, this can be compensated by an increased or decreased laser power. For 3D lay-up it can be useful to vary the lay-up speed around corners, if possible by the robot kinematics (see section 3.3) without changing the laser power proportionately. This can reduce the heating time of the substrate behind a convex corner.

3. 3D Test Specimens

3.2. Material and Lay-up Parameters

Within this study carbon fiber reinforced polyamide tape, Celstran® CFR-TP PA6 CF60-01 from Celanese (Sulzbach, Germany), with a tape width of 12 mm and a fibre volume content of 48 % was used [11]. The toolings were made of 2 mm thick steel sheets and were not heated.
The lay-up parameters for the test specimens can be found in Table 1.

Table 1. Lay-up parameters for 3D test specimens.

Parameter Name	Parameter Value
Lay-up Speed	75 mm/s
Compaction Force	130 N
Set Point Temperature	300°C
Initial Laser Angle to Substrate	24.5°
Cosed Loop Control Laser Angle	“ON”, after first layer
Closed Loop Control Laser Power	“ON”

3.1. Lay-up Geometry of Test Specimens

2 mm thick UD laminates, consisting of 18 layers, were manufactured with three different geometries based on ASTM 6415. The leg angles were 90°, 105° and 120° respectively while the inner radius of the specimens was 6.5 mm. Sufficent leg lengths were chosen to achieve a stable lay-up process before reaching the corner.
Figure 4 shows a lay-up sequence of the manufacturing of a set of 90° specimens.

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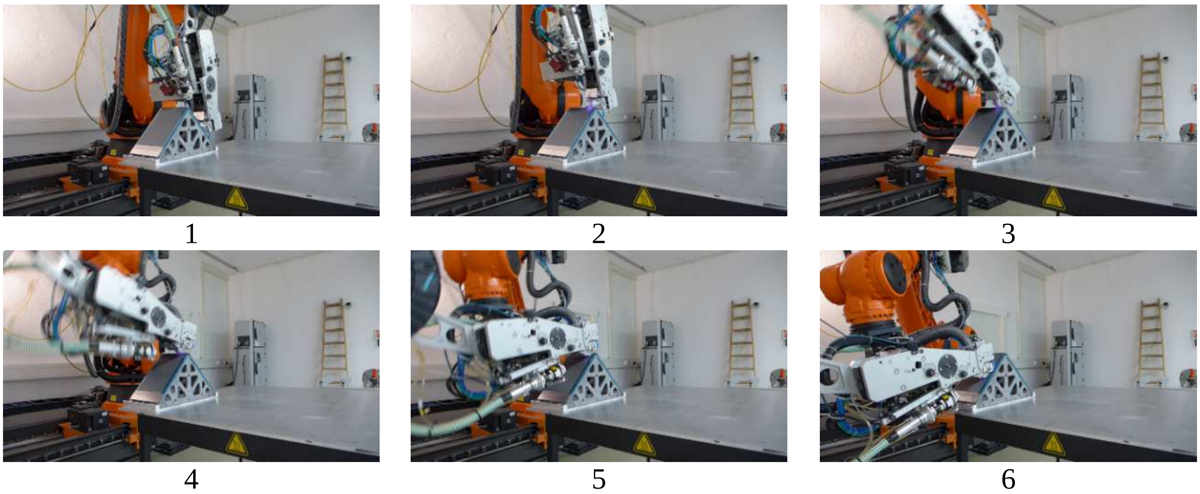

Figure 4. Lay-up sequence for 90° specimen

Three specimens were manufactured in parallel and cut afterwards by a watercooled diamond circular saw.

3.3. Manufacturing Process for 3D Specimens

Figure 5 shows the representative logfile data from a track in the middle of the lay-up of a 90° specimen (track 6 of layer 12). The process temperature, laser power, compaction roller deflection, robot's Tool Center Point (TCP)-speed and z-coordinate and the resulting tape-speed are plotted along the lay-up direction.

It can be clearly seen that the robot's speed drops around the corner and regains 100 % after about 30 mm. Additionally the deflection of the flexible roller, which is pressed on the tooling by a pneumatic cylinder changes by about 7.5 mm. These two effects add up with each other and cause a big drop in tape-speed. Suddenly slower tape-speed increases the time of the incoming tape remaining in the laser spot which causes overheating of the incoming tape.

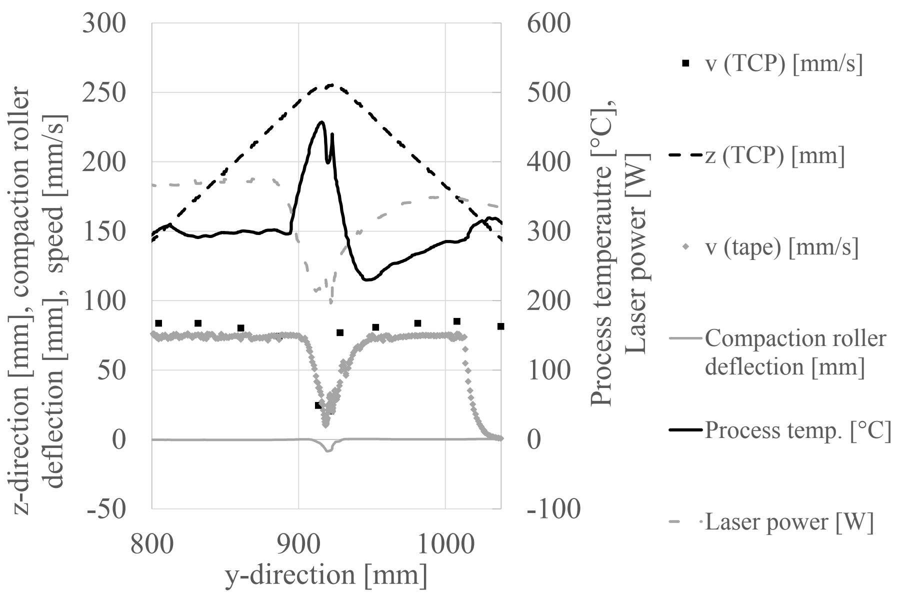

Figure 5. Logfile of track from 90° specimen

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The drop in the TCP-speed of the robot is caused by the need of a strong change of the robot's orientation around the corner (compare Figure 4). This effect is less critical for the specimens with 105° and 120°. The big deflection of the compaction roller is caused by the robot programming to enable such big changes of orientation in a short distance at high speed. The robot is blending its path trajectory, programmed by individual points. The blending causes TCP deviations from the intended path, which are compensated by the compaction roller's suspension, causing the deflection. However, without blending the robots trajectory no smooth movement of the robot would be possible.

The biggest process deviation from steady-state 2D lay-up can be seen in the substrate temperature. With the nip point getting closer to the corner, the backside of the corner already gets illuminated. The geometry induces an almost halt of the laser spot movement on the substrate which causes an overheating of the substrate on the backside of the corner in lay-up direction. This overheating is detected by the closed loop control which then drops the laser power to compensate this. Following this, the robot turns around the corner. Now, the lack of laser power induces a lack of process temperature in the substrate as well as in the incoming tape. Once the closed loop control determines the lack of temperature, the normal 2D process is obtained again for the flat part on the backside of the geometry. This effect can be seen on the test specimens. The frontsides of the specimens show a smooth and closed surface, while the backsides reveal gaps between the individual tracks in the region right behing the corner (Figure 6), due to less transverse squeeze flow of the tape.

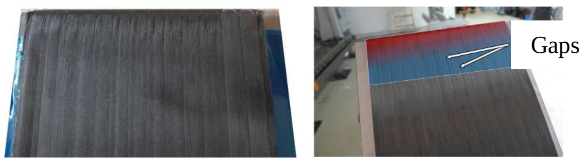

Figure 6. Photo of the frontside (left) and backside (right) of the corner during lay-up of 90° specimens with highlighted too hot and too cold regions

The change of heated area ($A_{illuminated}$) on the substrate during lay-up around the corner can be seen in the thermal camera image sequence in Figure 7. The projected laser spot size decreases right before the nip point reaches the corner (see picture 1-4 in Figure 7). This causes a local increase of laser intensity as stated in section 2.3. Additionally the deflection of the compaction roller causes a wrong laser spot distribution for the incoming tape and substrate (picture 5 in Figure 7).

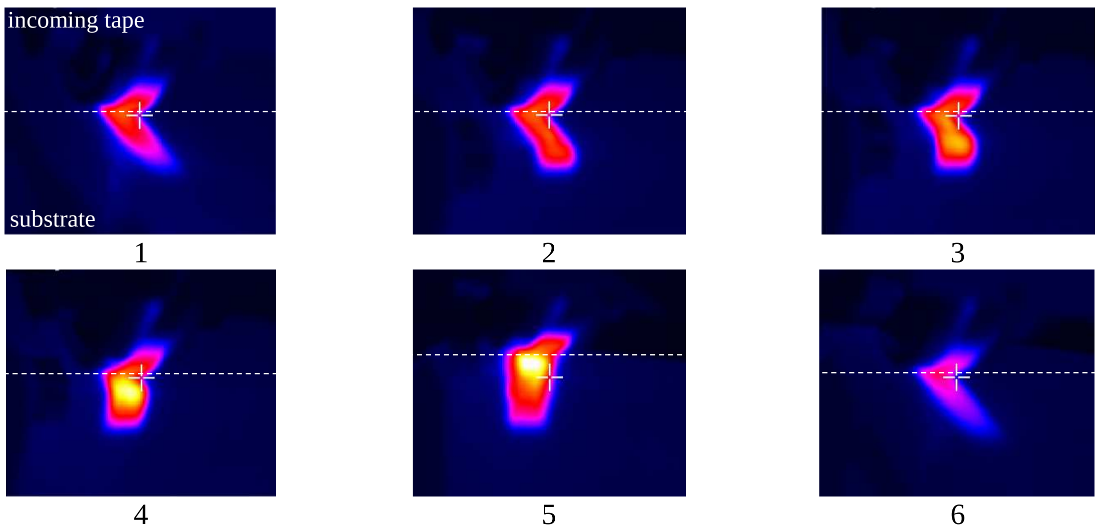

Figure 7. Thermal camera images of the nip point during lay-up around the corner of a 90° specimen

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A test lay-up of the 90° specimen with constant laser power of 300 W confirms this hypothesis. The laminate overheated strongly around the corner and went over to normal process after the corner.
As for other composite production methods, the thickness around the corner is reduced as well. Compared to the flanges the laminate thickness at the corner is reduced by 18 % in average. The big thickness reduction can be explained by the high tape tension, the reduction of the pressure active zone under the compaction roller around the corner causing an increase of surface pressure by 50 %. Additionally, this is also promoted by the high substrate temperature at the corner reducing the matrix’s viscosity.

3.4. Mechanical Testing

A four-point-bending test based on ASTM 6415 was chosen to evaluate the geometries influence on laminate quality. The tests were perfomed with a universal testing machine. Before testing the specimens were dried in an oven at 60°C for 24 h.

A set of six specimens per angle was tested in a standard four-point-bending fixture with a loading bar diameter of 10 mm. Due to the geometry of the fixture recommended by ASTM 6415, it can not be used for specimens with 105° and 120° leg angle. In order to reduce friction between the test specimen and fixture the loading bars were greased before each test.
Figure 8 shows on the left side the test setup and a representative force – displacement curve for a 90° specimen. In contrast to the example given in ASTM 6415 for a UD specimen, a ductile behavior can be observed. The force increases beyond the 5 mm abort criterion by ASTM 6415.
Figure 8 (right) shows the test results for the out-of-plane radial tensile strength σ_r at initial delamination for the 90°, 105° and 120° specimens with standard deviation for each test series. Higher values are reached for less sharp leg angles. However, the values may not be compared directly due to the different specimen geometry. In agreement with the standard, failure is produced along the whole width of the specimens, before reaching 5 mm machine displacement and symmetrically along the corner.

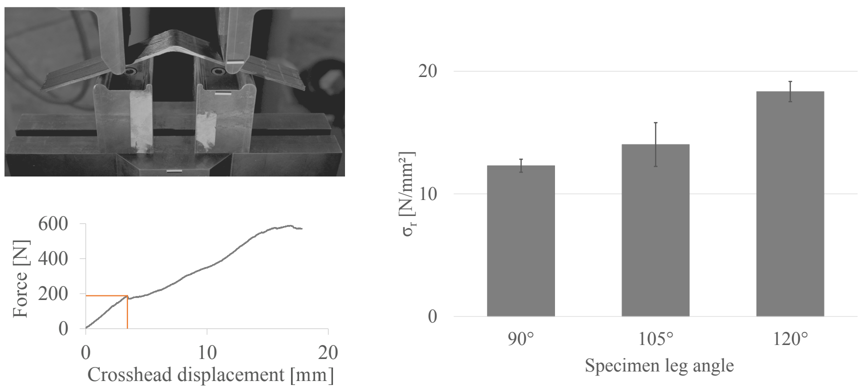

Figure 8. Left: Test setup and representative curve load-displacement for 90° specimen
Right: radial tensile strength σ_r of 90°, 105°, 120° specimens

The specimens show a ductile failure behavior with an increasing test force until they are deformed to an almost flat shape. Thermoplastics like PA6 are known to be more ductile than epoxy matix systems and especially TP-AFP manufactured specimens often show low crystallinity. Due to the fast cooling rate of the process the matrix stays in a mostly amorphous state.

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4. Conclusions

Based on 2D steady-state process parameters, 3D test specimens were manufactured by TP-AFP and mechanically tested. During manufacturing the 3D specimens, the substrate laminate gets too hot around the corner, which causes the closed loop power control to reduce the laser power immediately. The consequence of this drop in laser power is that the material on the following centimeters behind the corner is not sufficiently heated. Mechanical tests based on ASTM 6415 support these observations from the process log data.
Despite this behavior a laser control along the lay-up path is necessary. Both the laser power and its areal distribution need to be adapted to the 3D geometry. Only then equal heating might be possible even for complex 3D lay-up around sharp corners. This can be done either by a set of laser power values in a table for each geometry or by an intelligent closed loop control that can detect the heating disturbance of a convex 3D corner. Another challenge is to optimize the robots trajectory as the robot mounted laser optics needs to be kept in a constant position to the nip point and compaction roller. Besides more constant heating also the fiber alignment would benefit by this.

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References

[1] Stokes-Griffin CM, 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*; 78:274–83, 2015.
[2] Grouve W, Warnet LL, Rietman B, Akkerman R. On the weld strength of in situ tape placed reinforcements on weave reinforced structures. *Composites Part A*; 43(9):1530–6, 2012.
[3] Comer AJ, Ray D, Obande WO, Jones D, Lyons J, Rosca I et al. Mechanical characterisation of carbon fibre–PEEK manufactured by laser-assisted automated-tape-placement and autoclave. *Composites Part A*; 69:10–20, 2015.
[4] Barasinski A, Leygue A, Soccard E, Poitou A, Chinesta F, Chastel Y et al. An Improvement in Thermal Modelling of Automated Tape Placement Process. *International Conference on Advances in Materials and Processing Technologies*, p. 185–90, 2010.
[5] Qureshi Z, Swait T, Scaife R, El-Dessouky HM. In situ consolidation of thermoplastic prepreg tape using automated tape placement technology: Potential and possibilities. *Composites Part B*; 466:255–67, 2014.
[6] Grouve W, Warnet LL, Rietman B, Visser HA, Akkerman R. Optimization of the tape placement process parameters for carbon–PPS composites. *Composites Part A*; 50:44–53, 2013.
[7] August Z, Hauber D. Additive Manufacturing of High Performance Compsite Structures, 2014.
[8] Schledjewski R. Thermoplastic Tape Placement - Challenging the Autoclave Process: *EUCOMAS*, Berlin, 2008.
[9] Radlmaier V, Obermeier G, Ehard S, Kollmannsberger A, Koerber H, Ladstaetter E. Interlaminar Fracture Toughness of Carbon Fiber Reinforced Thermoplastic In-situ Joints; *PPS Conference*, Graz, Austria, 2015.
[10] Henne F, Ehard S, Kollmannsberger A, Hoeck B, Sause MG, Obermeier G, Drechsler K. Thermoplastic in situ fiber placment for future solid rocket motor casing manufacturing; *SAMPE Europe SETEC 14*, Tampere, Finland, 2014.
[11] Celanese Corporation. Technical Data Sheet: Celstran® CFR-TP PA6 CF60-01, 2014.

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