The Effects of Processing Parameters on the Wedge Peel Strength of CF/PEEK Laminates Manufactured Using a Laser Tape Placement Process

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Abstract

Manufacturing thermoplastic composites (TPC) with excellent mechanical properties requires advanced methods with reduced costs and better overall efficiencies. In this study, fiber-reinforced thermoplastic polymer composite laminates were manufactured using an automated fiber placement (AFP) manufacturing technology. The effects of processing temperature (from 320 ℃ to 500 ℃), lay-up speed (from 20 mm/s to 260 mm/s), consolidation force (from 100 N to 600 N), and prepreg tape tension (from 0 N to 9 N) on the quality of the resulting laminates manufactured using the laser AFP system were investigated. The interlayer bond strength was characterized using wedge peel tests on samples prepared with different process parameters. The studies were complemented by measurements of the thermal properties of the composites using different scanning calorimetry. The optimized process parameter windows were determined to be 360 ℃ to 400 ℃ for the irradiation temperature, 140 mm/s to 160 mm/s for the lay-up speed, 100 N for the consolidation force, and 3 N to 5 N for the prepreg tape tension, respectively. The microscopic analysis of the cross-sections and peel-damaged surfaces revealed that the different distributions of the resin matrix resulting from the different processing parameters affected the interlayer strength. These results may provide an important reference for manufacturing TPC used in aerospace, defense, and automotive applications.

1. Introduction

Carbon fiber reinforced thermoplastic polymer composites (CFRTPCs) as an advanced material used in the automotive, aerospace and mechanical industries for their advantageous properties including their lightweight, high resistance to impact damage, free-form methods and recyclability [1-4]. However, common manufacturing processes such as autoclave molding cannot access the high temperatures and pressures needed to mold TPC [5,6]. As such, molding processes that provide higher temperatures and pressures are instead used to mold TPCs [7,8]. However, the high costs of manufacturing the molds and the inability to mold complex parts are unavoidable shortcomings of these processes [9,10]. Therefore, the development of low cost and automated manufacturing processes for CFRTPs is the focus of many current research efforts.

AFP provides an automated and flexible additive manufacturing solution for TPCs [11-15]. Modern AFP manufacturing processes typically use a high power near-infrared (NIR) diode laser as a high-temperature heat source to reach the melting point of TPCs and bond the incoming tape with the substrate [11,12,16]. Literature studies on the processing-property relationships for AFP manufacturing carbon fiber (CF)-based TPCs have focused on high-performance thermoplastic matrices such as polyetheretherketone (PEEK) [17-21], polyphenyl sulfide (PPS) [22-25], polyetherimide (PEI) [26,27], polytherketone (PEKK) [28,29], or polyethersulfone (PES) [30]. PEEK matrices are more resistant to high temperature and chemical corrosion than other thermoplastic matrices, and as such, the majority of publications have focused almost exclusively on modeling AFP-related processing of CF/PEEK materials such as bonding, void dynamics, crystallization, residual stress development, and degradation. For example, Levy et al. [31] investigated the link between the degree of intimate contact and the consequent thermal contact

resistance between layers. Based on their results, they proposed a relationship and determined the missing parameter for APC2 thermoplastic prepreg composites through a hot plate forming process experiment. Stokes-Griffin [32] investigated the mechanical properties of samples obtained by controlling the laser irradiation temperature in the range of 400 ℃ to 600 ℃ for lay-up experiments with lay-up speeds of 100 mm/s and 400 mm/s. It was found that degradation occurred at an irradiation temperature of 600 ℃ and a lay-up speed of 100 mm/s, but no degradation was observed at a lay-up speed of 400 mm/s. Stokes-Griffin et al. [33] also investigated the effect of the laser irradiation temperature on the quality of TPCs laminates manufactured with an automated tape placement (ATP) system. They observed a reduction in the wedge peel strength at high temperatures due to extrusion of the low viscosity polymers from the samples under pressure and not due to thermal degradation of the TPCs. Oromiehie et al. [14] used a hot-gas torch (HGT) as the heating source for manufacturing high-quality TPCs laminates, and the lay-up parameters were optimized. They found that the optimum mechanical properties were obtained by increasing the HGT temperature and consolidation force to a certain level, but too high of an HGT temperature (950 ℃) or consolidation force (450 N) caused severe fiber damage. Despite the number of studies, detailed process parameters have not been discussed, yet these parameters directly affect the fiber-resin bonded interface, resin distribution, fiber breakage, and void defects in AFP manufactured CFRTPC samples. Therefore, optimization of the lay-up process parameters will allow for the manufacturing of samples that meet the low-cost and high mechanical performance needs.

Herein, CFs and PEEK were used as the reinforcement and thermoplastic matrix for AFP additive manufacturing, respectively. The entire lay-up process includes CF/PEEK prepreg slitting, clamping, re-feeding, shearing and irradiation curing stages. The wedge peel strength was used to characterize the effects of different processing parameters on the interlaminar strength. Ultimately, the feasibility and versatility of the proposed technology were demonstrated by laying tests of samples prepared using the optimized process parameters.

2. Experimental Methods

2.1. Laser AFP system

Placement tests were performed using an AFP system for TPCs as depicted in Fig.1. A NIR diode laser provided the heat needed for the lay-up process. The CF/PEEK prepreg was then layered under the heat provide by the NIR diode laser. The laser irradiation spot size was 13×45 mm with a focal length of 400 mm. The temperature of the laser irradiation spot was set by the control software, and real-time temperature feedback during operation was provided through a pyrometer with a measurement range of 220-1418.2 ℃ to ensure that the irradiation temperature was within the set temperature range. In order to ensure that there was sufficient irradiation area of the substrate prepreg and the incoming CF/PEEK tape, the laser heating mechanism could be adjusted over a range of angles from 10-32.5°, and the laser incidence angle was set to 22.5° based on previous experience. Compression force was provided by a silicone rubber roller in the placement head section, allowing for a tighter compression of the PEEK resin

under laser irradiation. The CF/PEEK prepreg wound on the reel was guided, clamped, re-fed, and sheared, resulting in layers of CF/PEEK prepregs stacked on top of one another.

The temperature field during the lay-up process was calibrated using a Filr X6520sc high-end medium - wave cooled infrared camera (temperature range 5 ℃ to 1500 ℃, accuracy ±1 ℃). Fig.2 shows the measured temperature distribution in the lay-up field. As shown in Fig.2, the temperature at the nip-point exceeded the melt temperature (343 ℃) of the PEEK resin, ensuring that the upper and lower layers of CF/PEEK prepreg were laminated.

2.2. Placement trials

The CF/PEEK prepreg used in the experiments had a PEEK mass fraction of 55%. The prepreg with a size of 0.09×10 mm was provided by Shandong University of Technology, China and was cut and used for lay-up. Single variable experiments were conducted by varying one of the four processing parameters, including the laying temperature (T), laying speed (V), compression force of the pressure roller (Fc) and prepreg tension (Ft), during the preparation of the lay-up samples, and the remaining parameters were kept constant as shown in Table 1.

Table 1. Process parameter setting during AFP manufacturing laminates.

Variable parameters	Initial	incremental	Final	Constant parameters		
T/°C	280	20	500	V/(mm•s^{-1}) 100	F_c/N 300	F_t/N 3
V/(mm•s^{-1})	20	20	260	T/°C 400	F_c/N 300	F_t/N 3
F_c/N	100	100	600	T/°C 400	V/(mm•s^{-1}) 100	F_t/N 3
F_t/N	0,1	2	9	T/°C 400	V/(mm•s^{-1}) 100	F_c/N 300

The temperature was controlled by changing the irradiation temperature set point in the software. The compression force was provided by a cylinder inside the AFP head, and the prepreg tension was controlled and adjusted by a magnetic powder brake in the reel section. First, a layer of polyimide (PI) film was placed on the tooling to facilitate better bonding between the CF/PEEK prepreg and the aluminum plate tooling [34-36]. After which, the first layer of unidirectional prepreg was placed on the PI film, and a second layer was laid on top of the first layer to form a $[0]_2$ laminate. The third layer was laid on top of the second layer to form a $[0]_3$ laminate. To form a non-adhesive region in the sample for crack extension, a PI film with dimensions of 120×12 mm was manually placed at the end of the third prepreg, and then a fourth prepreg layer was laid on top to obtain $[0]_4$ laminate. The layer sequence was repeated to obtain a $[0]_6$ laminate. The final laminate length was 320 mm, and the length of the non-bonded area formed by the PI film was 120 mm. The experiment was repeated, and three samples under the same working condition were prepared to determine the reproducibility of the results. The original width of each group of samples was measured five times, and the average value was taken as the original average width. Considering that the sample position was offset during the lay-up process and the fluidity of the PEEK resin increased under laser irradiation, the resulting increase in the original sample width was not the

sample width of the prefabricated crack expansion in the wedge peel test. Therefore, the lay-up samples were pruned, and the sample width was recorded and used to determine the wedge peel strength. The same set of samples was tested at a total of 15 different locations along the lengths of the samples, and the reported width is the average of the 15 values.

2.3. Characterization of the inlayer bonding strength

The AFP process requires an interlayer bonding step, and the quality of the formed interlayer bond is a critical determinant of the laminate performance. The ASTM D2344 short beam strength (SBS) test is usually used to determine interlaminar strength of composites formed by AFP because the measurement is sensitive to the resin properties and interlaminar bond strength [37,32]. However, plastic deformation in thermoplastic resins during SBS tests complicates the interpretation of the results because the measured value also contains additional contributions from shear failure of the thermoplastic matrix, and thus the measured strength is lower and does not reflect only failure due to interlaminar crack formation. Therefore, an alternative method, known as the wedge peel test, has been used to measure the interlaminar strength of AFP fabricated parts, and the results of the wedge peel test correlate well with the results from double cantilever beam (DCB) tests that are commonly used to characterize the interlaminar bond quality in automatic lay-up related studies [38].

The wedge peel test was performed using the device shown in Fig.3. The prefabricated crack formed by the PI film between the third and fourth layers was passed through a rounded edge wedge with an angle of 30°. The sample was clamped by the upper fixture and raised at a speed of 1mm/s, causing the prefabricated crack in the sample to expand. The resulting force-displacement curve was measured using a 30 kN load cell and a PLD-5 (MTS Systems Co., Ltd., China) universal testing machine at 50 Hz. The force measured by the sensor during the test was the wedge peel force.

Typical force-displacement curves measured for three samples prepared for the single variable tests using an irradiation temperature of 400 ℃, a laying speed of 120 mm/s, a press roll compression force of 600 N and a prepreg tension of 9 N are shown in Fig.5a-d. For the tests, when one of the four parameters was varied, the other parameters were held constant at a heating temperature of 400 ℃, a laying speed of 100 mm/s, a compression force of 300 N and a prepreg tension of 3 N. After the measured wedge peel force stabilized, sample sections for statistical analysis were selected, and the average wedge peel force value was calculated and normalized by the average width of the specimen.

2.4. Different scanning calorimetry

Different scanning calorimetry (DSC) measurements in this work were used to determine any variation in properties that indicated a change in the molecular structure of the samples due to thermal degradation of the polymer, such as changes in melting and crystallization temperatures. The transition temperatures seen in CF/PEEK composites are the glass transition temperature, the melting temperature, the decomposition temperature, and the crystallization temperature and identify the transitions between the glassy, highly elastic-viscous flow state of the PEEK matrix and the decomposition of the PEEK matrix in

CF/PEEK materials [39-41]. DSC measurements were performed using a DSC1 instrument (METTLER TOLEDO Ltd., Switzerland). The measurements were performed in a nitrogen-protected atmosphere, and the sample was heated from room temperature to 500 ℃ at a heating rate of 10 ℃/min, held for 30 s, and then cooled to room temperature at the same rate. The DSC curves were then analyzed to record the melting point of the composite as well as the degree of crystallinity. The degree of crystallinity was calculated according to the following equation:

$$\%X_C = \frac{\Delta H_f}{H_{f0} \times w_f} \times 100 \quad (1)$$

Where ΔH_f is enthalpy of fusion of PEEK (55.8 J/g), H_{f0} is the heat of fusion of 100% crystalline PEEK (130 J/g) and W_f is the weight fraction of PEEK in composites.

3. Results And Discussion

3.1. Wedge peel strength

To determine the relationship between the actual temperature of the device during the sample lay-up and the set temperature, statistical analysis was conducted on the measured temperature, and the results of this analysis are shown in Fig.4. The results showed that the standard deviation between the set and measured temperatures was less than 2.5 ℃ at any set point temperature, which was sufficient accuracy for the process temperature.

Wedge peel tests were conducted on all samples prepared during the single variable experiments to determine the effects of the irradiation temperature, laying speed, compression force of the roller, and prepreg tension on the resulting interlayer bond strength. The force-displacement curves from the wedge peel tests of the selected sample areas agreed well amongst all samples prepared with the studied processing conditions, as shown in Fig.5. Ideally, the force-displacement curves of the three different samples prepared with the same process parameters should overlap; however, due to errors in the lay-up process this was not the case in the present experiments. Instead, segments of the measured force-displacement curve that overlapped were selected for normalization.

The force-displacement curves were analyzed, and the average wedge peel force of each group of samples was obtained. The wedge peel strengths of the samples prepared with different process parameters were calculated as $S = F / b$, where *S*, *F*, and *b* denote the wedge peel strength, wedge peel force, and sample width, respectively. To make the results more reliable and accurate, the b values used were the uniformly processed widths. The width averages are shown as lines in Fig.6, and the bars represent the sample wedge peel strength.

As seen in Fig.6, the widths of all treated samples were consistently around 10 mm. As can be seen from the above Fig.6a, when the processing temperature was lower than 340 ℃, the wedge peel strength of the sample was low, indicating that the layers did not bond during the laying processing step. When the processing temperature was in the range of 360 ℃ to 400 ℃, the wedge peel strength was higher and on the order of 3.22 N•mm^{-1}, indicating that the interlayer bonding was stronger. At an even higher processing temperature of 420 ℃, the wedge peel strength was 2.4 N•mm^{-1}, indicating that the interlayer strength had decreased significantly. As the process temperature continued to rise to 500 ℃, the interlayer strength continued to rise. When the process temperature exceeded 500 ℃, white smoke was observed during the lay-up process, suggesting possible decomposition of the PEEK matrix.

The internal structures and pore distributions of the samples processed 320 ℃, 400 ℃, and 500 ℃ were imaged using a micro X-ray 3D imaging system (YXLON International GmbH, Hamburg, Germany) at an accelerating voltage of 80 kV with an image resolution of 8.0 μm, and the results are shown in Fig.7. The sample processed at a lay-up temperature of 400 ℃ had the lowest porosity of 18.01%, indicating that there were minimal defects between layers at this temperature. Different degrees of damage and defects were seen between the layers in the samples processed at both 320 ℃ and 500 ℃, which was also reflected in the unstable wedge peel test results. The analysis suggested that the low viscosity of the PEEK matrix in the low temperature (320 ℃) lay-up conditions and insufficient compaction led to interlayer defect damage, while PEEK matrix decomposition at higher processing temperatures (500 ℃) and the larger degree of flexural deformation and crystallization shrinkage lead to the formation of more interlayer defects.

As can be seen in the results in Fig.6b, the wedge peel strength of the samples increased with the lay-up speed above 20 mm/s and reached a maximum value of 3.04 N•mm^{-1} in the sample produced with a lay-up speed of 140 mm/s. This value was 79.88% higher than the wedge peel strength of the sample manufacture with the lowest placement speed. The wedge peel strength remained high for the sample prepared with a lay-up speed was 160 mm/s and decreased with placement speeds greater than 160 mm/s. These results indicate that too fast of a lay-up speed may results in insufficient bonding between the layers of PEEK matrix.

As can be seen in the results in Fig.6c, the sample wedge peel strength of the sample prepared with a lay-up compression force of 100 N was 3.12 N•mm^{-1}. The interlayer strength was higher in samples prepared using this processing condition; however, as the compression force increased, the wedge peel strength decreased. The analysis indicated that when samples were processed with a lower pressure at a processing temperature of 400 ℃, the PEEK resin matrix had a lower energy storage modulus and did not outflow from the sides of the samples, and as a result, more resin remained in the interlayers of the sample. As the compression roller pressure increases, the PEEK matrix was extruded from the sample, reducing the amount of interlayer PEEK and leading to lower interlayer strengths.

As can be seen in from the results in Fig.6d, as the tension of CF/PEEK prepreg tape increased from 0 N, the wedge peel strength of the samples first increased and then decreased, reaching a maximum value of

3.29 N•mm^{-1} in the sample prepared with a prepreg tension was at 5 N. When the prepreg tension increased to 7 N and 9 N, the wedge peel strengths were 1.5 N•mm^{-1} and 1.54 N•mm^{-1}, decreasing by 54.41% and 53.19%, respectively. The analysis indicated that when samples were prepared with a CF/PEEK prepreg tension of 0 N, the PEEK substrate bonded the two layers of prepreg together under the pressure from the compression roller. Meanwhile, when the prepreg was under tension, the internal tension weakened the action of compression roller force, resulting in the less outward flow of the PEEK matrix from samples as shown in Fig.8. The resin overflow was lowest when the samples were prepared with a prepreg tension around 5 N, resulting in the best interlayer strength. As the prepreg tension increased further, internal tension hindered the bonding between the layers, decreasing the interlayer bonding, and thus reducing the interlayer strength.

3.2. Differential scanning calorimetry

The obtained DSC curves are shown in Fig.9, and from which it can be seen that the glass transition occurred between 151-183 ℃, the viscoelastic transition region was between 297-358 ℃, and the PEEK sample degraded when the temperature exceeded 500 ℃. Combining the DSC results with the results of the process temperature studies in Fig.6a, indicated that the PEEK matrix began to melt when the process temperature reached 297 ℃, but the matrix fluidity was low, and therefore, the interlayer adhesion was low. These DSC results combined with the results of the lay-up experiment indicated that there was visible non-bonding between the layers in the sample prepared at 320 ℃. However, when the process temperature was above 360 ℃, as can be seen in Fig.9, the temperature was close to the upper limit of the melting temperature range, and the PEEK resin matrix had a low energy storage modulus and good fluidity, resulting in high interlayer strength. As shown in Fig.6a, the wedge peel strength increased in samples processed above 360 °C, but at too high of a process temperature, the matrix was too fluid and the resin overflowed from the sample, leading to a decrease in the interlayer strength.

The results of the DSC tests conducted on the samples laid at different temperatures are shown in Fig.10. The results showed that the samples prepared at a temperature of 380 ℃ had higher degrees of crystallinity, indicating that the crystals within the PEEK matrix grew faster in this temperature range. In contrast, the degree of crystallinity decreased as the process temperature continued to increase, which may be due to the fact that more crystalline polymer regions melted and formed more of the amorphous phase at high temperatures, thus decreasing the degree of crystallinity.

3.3. Microscopic characterization

The cross-sections of the samples prepared under different prepreg tensions were observed with field emission electron microscopy SU-8010 (Hitachi Ltd., Japan), and the results are shown in Fig.11A. The sample prepared with a prepreg tape tension of 1 N was 583 μm, and as the prepreg tape tension increased to 5 N, the sample thickness increased to 625 μm. Gaps were seen in the cross section of the sample prepared with a prepreg tape tension of 9 N, which led to an increase in the laminate thickness to 828 μm. Combined with the analysis of the image results in Fig.8, it can be seen that increasing the

prepreg tape tension decreased the effects of the compression roller force, which in turn reduced the melt bonding between the PEEK matrix layers and ultimately led to a reduction in the interlayer bond strength seen as the reduced wedge peel strength in samples manufacture with higher prepreg tape tensions in Fig.6d. A laser confocal microscope Lext Ols4000(Olympus Ltd., Japan) was used to observe the three-dimensional morphology of the lay-up samples, and the results are shown in Fig.11B. Fig.11B (a)-(c) show the warpage and deformation in samples prepared with irradiation temperatures of 320 ℃, 400 ℃ and 500 ℃, respectively. It can be seen that when the temperature was 320 ℃, there were broken fibers on the lay-up surface, likely because of the low viscosity of the PEEK matrix and the low degree of compression of the resin, which led to brittle fracture of the CF fiber mixture wrapped around the PEEK matrix. When the temperature was 400 ℃, the lay-up surface was smooth. When the temperature reached 500 ℃, significant deformation was seen on the surface of the laminate. It was thought that the lower viscosity of the PEEK matrix at these high temperatures would lead to resin overflow out of the sides of the sample; however, on the contrary, the PEEK matrix accumulated in the middle of the sample, thus leading to a nonuniform sample thickness that was thicker in the middle and thinner on the sides, and an accompanying uneven stress distribution that caused the sample to warp. The original width of the sample after laying was measured, and the results are shown in Fig.11C. The results showed that the samples prepared with slower lay-up speeds were wider. When this trend is sample widths was considered along with the results of DSC analysis, the results indicate that the when the resin was in a molten state, a slower lay-up speed meant that the sample was under compression for a longer time, and more matrix material was squeezed of the sample, thereby increasing the sample width. As the pressure of the compaction roller increased and the prepreg tension decreased, the original width of the sample also increased due to changes in the extent of resin outflow.

Summary And Conclusion

The effects of processing parameters on the interlaminar strength of CF/PEEK laminates manufactured using an NIR lamp filament lay-up system were investigated. The inter-laminar bond strength was characterized by wedge peel tests on samples manufactured with different process temperatures (from 320 ℃ to 500 ℃), lay-up speeds (from 20 mm/s to 260 mm/s), compaction roller forces (from 100 N to 600 N), and prepreg tape tensions (from 0 N to 9 N). The changes in the CF/PEEK prepreg physical state with temperature were investigated by DSC. The fiber-matrix distribution in the sample cross-sections and the failed surfaces were characterized by SEM. The key findings of the study are as follows,

- Higher wedge peel strengths (all above 3.22 N•mm^{-1}) and higher interlaminar strengths were measured for laminates manufactured at lay-up irradiation temperatures in the range of 360 ℃ to 400 ℃, indicating that this temperature range is suitable for CF/PEEK prepreg lay-up.
- At the laying speed of 140 mm/s, the wedge peel strength achieved a maximum value of 3.04 N•mm^{-1}, which was 79.88% higher than the wedge peel strength of the sample obtained at the lowest laying speed. Samples with high interlayer strengths were obtained up to a laying speed of 160 mm/s, indicating the laying speed range of 140 mm/s to 160 mm/s is a suitable lay-up speed range.

- The studies of the effect of the compaction roller force on the interlayer strength showed that using a low applied pressure was conducive for increasing the interlayer strength, mainly because the matrix material was not extruded from the sample at low compaction roller pressures.
- Greater interlayer strengths were measured in samples prepared with prepreg tape tensions ranging from 3 N to 5 N, indicating that this range of tensions is suitable for sample processing.
- The DSC showed that the PEEK matrix melted between 297 ℃ to 358 ℃, and process temperature higher than the melting temperature lowered the resin matrix energy storage and viscosity, and the resin flowed more easily during processing. When the temperature exceeded 500 ℃, white smoke generated during the placement experiment showed that that the surface resin matrix decomposed.

The effects of the different process parameters on the interlayer strength showed that for low melt viscosity matrices, the main mechanism of mechanical property loss in the laminates was due to flow or extrusion of the matrix during processing. The matrix viscosity needs to be considered to constrain and optimize the processing parameters to produce lay-up samples with higher interlayer strengths. This finding is particularly significant for AFP process models. The wedge peel strength appeared to be sensitive to both the resin-rich interlaminar region and fiber distribution in the laminate. It would therefore be interesting to compare CF/PEEK prepregs processed under the same conditions with different resin volume fractions. Future work will continue to optimize the placement process for different types of CF/PEEK prepregs to ensure reliable production of CF/PEEK composite structures.

Declarations

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Author contribution

Chenping Zhang: Conceptualization, Methodology, Writing – Original Draft. **Yugang Duan:** Methodology, Writing – Review & Editing, Supervision. **Hong Xiao:** Writing -Review & Editing. **Yueke Ming:** Methodology, Writing -Review & Editing. **Yansong Zhu:** Investigation. **Fugan Zhang:** Investigation.

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References

1. Valino AD, Dizon JRC, Espera AH, Chen Q, Messman J, Advincula RC (2019) Advances in 3D printing of thermoplastic polymer composites and nanocomposites. Progress in Polymer Science 98:101162.

2. Penumakala PK, Santo J, Thomas A (2020) A critical review on the fused deposition modeling of thermoplastic polymer composites. Composites Part B: Engineering 201:108336.

3. Olmos D, González-Benito J (2007) Visualization of the morphology at the interphase of glass fibre reinforced epoxy-thermoplastic polymer composites. European Polymer Journal 43 (4):1487-1500.

4. Bhattacharjee Y, Biswas S, Bose S (2020) Chapter 5 - Thermoplastic polymer composites for EMI shielding applications. In: Joseph K, Wilson R, George G (eds) Materials for Potential EMI Shielding Applications. Elsevier, pp 73-99.

5. Santoro D, Bellisario D, Quadrini F, Santo L (2020) Anisogrid thermoplastic composite lattice structure by innovative out-of-autoclave process. The International Journal of Advanced Manufacturing Technology 109 (7):1941-1952.

6. Saenz-Castillo D, Martín MI, García-Martínez V, Ramesh A, Battley M, Güemes A (2020) A comparison of mechanical properties and X-ray tomography analysis of different out-of-autoclave manufactured thermoplastic composites. Journal of Reinforced Plastics and Composites 39 (19-20):703-720.

7. Asim M, Jawaid M, Saba N, Ramengmawii, Nasir M, Sultan MTH (2017) 1 - Processing of hybrid polymer composites—a review. In: Thakur VK, Thakur MK, Gupta RK (eds) Hybrid Polymer Composite Materials. Woodhead Publishing, pp 1-22.

8. Pantani R, Coccorullo I, Speranza V, Titomanlio G (2005) Modeling of morphology evolution in the injection molding process of thermoplastic polymers. Progress in Polymer Science 30 (12):1185-1222.

9. Sposito A, Hoang V, DeVoe DL (2016) Rapid real-time PCR and high resolution melt analysis in a self-filling thermoplastic chip. Lab on a Chip 16 (18):3524-3531.

10. Pantelakis SG, Katsiropoulos CV, Labeas GN, Sibois H (2009) A concept to optimize quality and cost in thermoplastic composite components applied to the production of helicopter canopies. Composites Part A: Applied Science and Manufacturing 40 (5):595-606.

11. Baho O, Ausias G, Grohens Y, Férec J (2020) Simulation of laser heating distribution for a thermoplastic composite: effects of AFP head parameters. The International Journal of Advanced Manufacturing Technology 110 (7):2105-2117.

12. Chen J, Fu K, Li Y (2021) Understanding processing parameter effects for carbon fibre reinforced thermoplastic composites manufactured by laser-assisted automated fibre placement (AFP). Composites Part A: Applied Science and Manufacturing 140:106160.

13. Dhinakaran V, Surendar KV, Hasunfur Riyaz MS, Ravichandran M (2020) Review on study of thermosetting and thermoplastic materials in the automated fiber placement process. Materials Today: Proceedings 27:812-815.

14. Oromiehie E, Gain AK, Prusty BG (2021) Processing parameter optimisation for automated fibre placement (AFP) manufactured thermoplastic composites. Composite Structures 272:114223.

15. Schuster A, Mayer M, Willmeroth M, Brandt L, Kupke M (2020) Inline Quality Control for Thermoplastic Automated Fibre Placement. Procedia Manufacturing 51:505-511.

16. Peeters D, Deane M, O'Higgins R, Weaver PM (2020) Morphology of ply drops in thermoplastic composite materials manufactured using laser-assisted tape placement. Composite Structures 251:112638.

17. Velu R, Vaheed N, Ramachandran MK, Raspall F (2020) Experimental investigation of robotic 3D printing of high-performance thermoplastics (PEEK): a critical perspective to support automated fibre placement process. The International Journal of Advanced Manufacturing Technology 108 (4):1007-1025.

18. Hosseini SMA, Baran I, van Drongelen M, Akkerman R (2021) On the temperature evolution during continuous laser-assisted tape winding of multiple C/PEEK layers: The effect of roller deformation. International Journal of Material Forming 14 (2):203-221.

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

20. Baho O, Ausias G, Grohens Y, Barile M, Lecce L, Férec J (2021) Automated fibre placement process for a new hybrid material: A numerical tool for predicting an efficient heating law. Composites Part A: Applied Science and Manufacturing 144:106360.

21. Arns J-Y, Oromiehie E, Arns C, Prusty BG (2021) Micro-CT analysis of process-induced defects in composite laminates using AFP. Materials and Manufacturing Processes:1-10.

22. Grouve WJB, Warnet LL, Rietman B, Visser HA, Akkerman R (2013) Optimization of the tape placement process parameters for carbon–PPS composites. Composites Part A: Applied Science and Manufacturing 50:44-53.

23. Geng P, Zhao J, Wu W, Wang Y, Wang B, Wang S, Li G (2018) Effect of Thermal Processing and Heat Treatment Condition on 3D Printing PPS Properties. Polymers 10 (8).

24. Barbosa LCM, de Souza SDB, Botelho EC, Cândido GM, Rezende MC (2019) Fractographic evaluation of welded joints of PPS/glass fiber thermoplastic composites. Engineering Failure Analysis 102:60-68.

25. Batista NL, Olivier P, Bernhart G, Rezende MC, Botelho EC (2016) Correlation between degree of crystallinity, morphology and mechanical properties of PPS/carbon fiber laminates. Materials Research 19 (1):195-201.

26. Dai SC, Ye L (2002) Characteristics of CF/PEI tape winding process with on-line consolidation. Composites Part A: Applied Science and Manufacturing 33 (9):1227-1238.

27. Hou M, Ye L, Lee HJ, Mai YW (1998) Manufacture of a carbon-fabric-reinforced polyetherimide (CF/PEI) composite material. Composites Science and Technology 58 (2):181-190.

28. Çelik O, Peeters D, Dransfeld C, Teuwen J (2020) Intimate contact development during laser assisted fiber placement: Microstructure and effect of process parameters. Composites Part A: Applied Science and Manufacturing 134:105888.

29. Doll G Thermoplastic composites technologies for future aircraft structures. In: Liebl J (ed) Vehicles of Tomorrow 2019, Wiesbaden, 2021// 2021. Springer Fachmedien Wiesbaden, pp 129-138

30. Kollmannsberger A, Lichtinger R, Hohenester F, Ebel C, Drechsler K (2017) Numerical analysis of the temperature profile during the laser-assisted automated fiber placement of CFRP tapes with thermoplastic matrix. Journal of Thermoplastic Composite Materials 31:089270571773830.

31. Levy A, Heider D, Tierney J, Gillespie JW (2013) Inter-layer thermal contact resistance evolution with the degree of intimate contact in the processing of thermoplastic composite laminates. Journal of Composite Materials 48 (4):491-503.

32. Stokes-Griffin CM, Compston P (2015) 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 78:274-283.

33. Stokes-Griffin CM, Kollmannsberger A, Compston P, Drechsler K (2019) The effect of processing temperature on wedge peel strength of CF/PA6 laminates manufactured in a laser tape placement process. Composites Part A: Applied Science and Manufacturing 121:84-91.

34. Venkatesan C, Velu R, Vaheed N, Raspall F, Tay T-E, Silva A (2020) Effect of process parameters on polyamide-6 carbon fibre prepreg laminated by IR-assisted automated fibre placement. The International Journal of Advanced Manufacturing Technology 108 (4):1275-1284.

35. Del Castillo DS, Martin I, Rodriguez-Lence F, GUEMES A On-line monitoring of a laser-assisted fiber placement process with CFR thermoplastic matrix by using fiber Bragg gratings. In: 8th European workshop on structural health monitoring (EWSHM 2016), 2016.

36. Hosseini SA, Baran I, van Drongelen M, Akkerman R (2021) On the temperature evolution during continuous laser-assisted tape winding of multiple C/PEEK layers: The effect of roller deformation. International Journal of Material Forming 14 (2):203-221

37. Comer AJ, Ray D, Obande WO, Jones D, Lyons J, Rosca I, O' Higgins RM, McCarthy MA (2015) Mechanical characterisation of carbon fibre–PEEK manufactured by laser-assisted automated-tape-placement and autoclave. Composites Part A: Applied Science and Manufacturing 69:10-20.

38. Azab M, Parry G, Estevez R (2020) An analytical model for DCB/wedge tests based on Timoshenko beam kinematics for accurate determination of cohesive zone lengths. International Journal of Fracture 222 (1):137-153

39. Yan T, Yan F, Li S, Li M, Liu Y, Zhang M, Jin L, Shang L, Liu L, Ao Y (2020) Interfacial enhancement of CF/PEEK composites by modifying water-based PEEK-NH2 sizing agent. Composites Part B: Engineering 199:108258.

40. Lu C, Xu N, Zheng T, Zhang X, Lv H, Lu X, Xiao L, Zhang D (2019) The Optimization of Process Parameters and Characterization of High-Performance CF/PEEK Composites Prepared by Flexible CF/PEEK Plain Weave Fabrics. Polymers 11 (1).

41. Yan M, Tian X, Peng G, Li D, Zhang X (2018) High temperature rheological behavior and sintering kinetics of CF/PEEK composites during selective laser sintering. Composites Science and Technology 165:140-147.

Figures

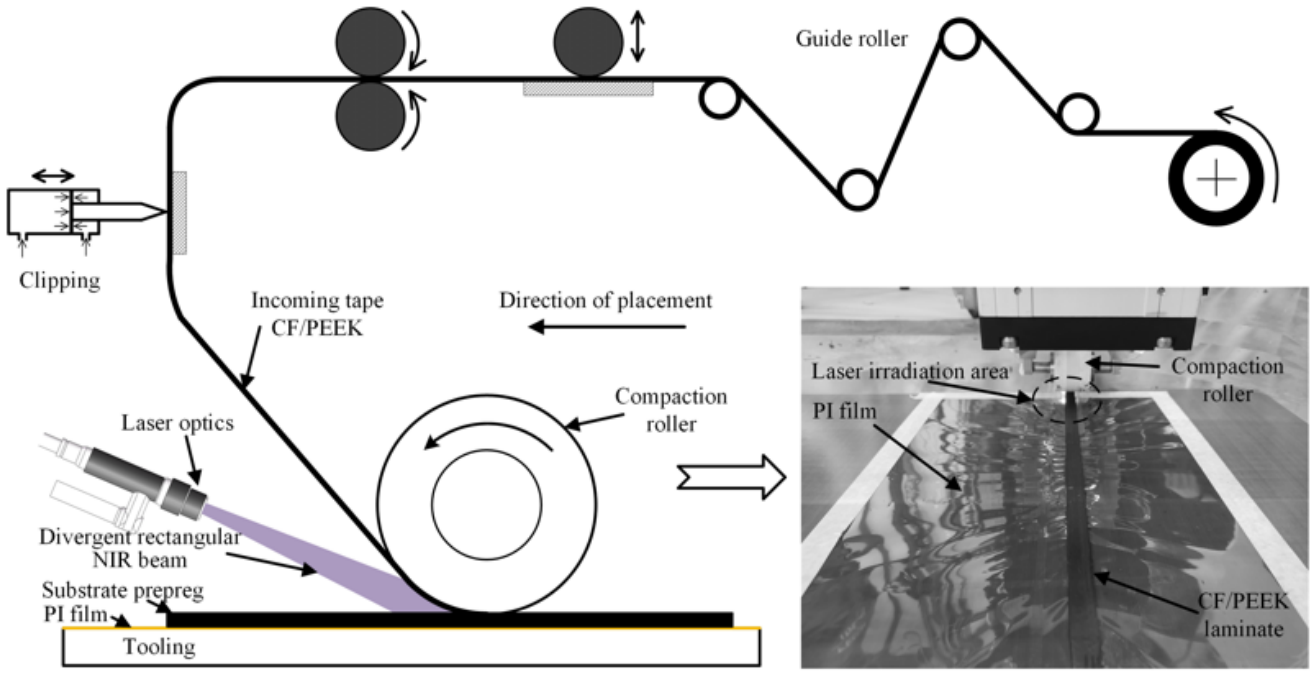

Figure 1

Schematic image of the laser AFP manufacturing process schematic using a nip-point heating strategy.

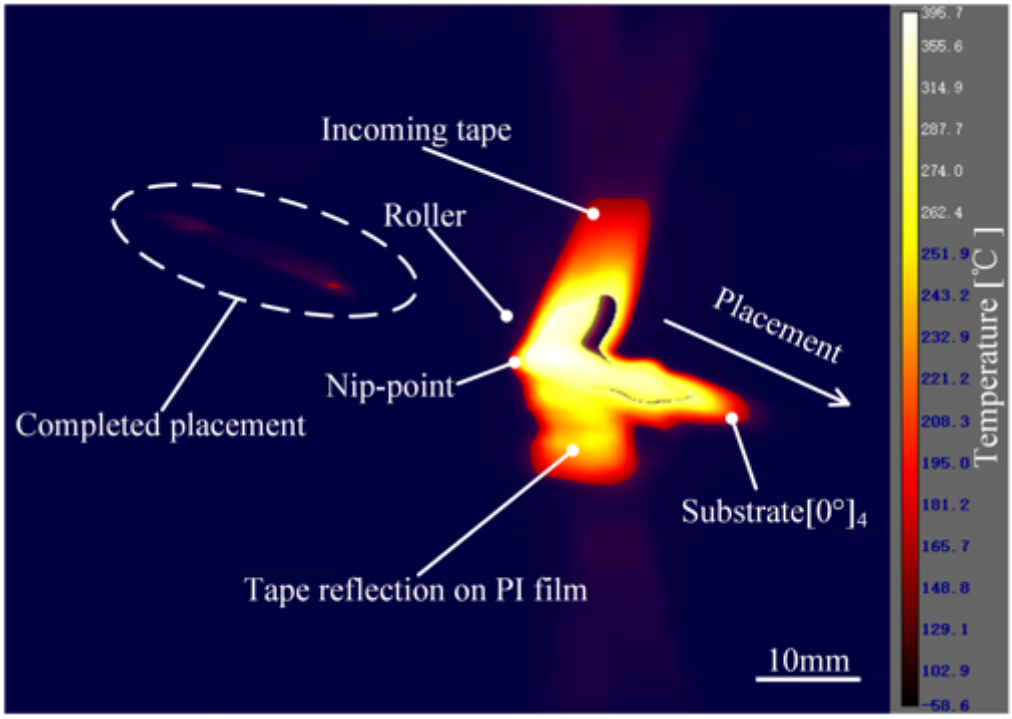

Figure 2

Typical temperature field distribution during the AFP process for laying CF/PEEK prepreg.

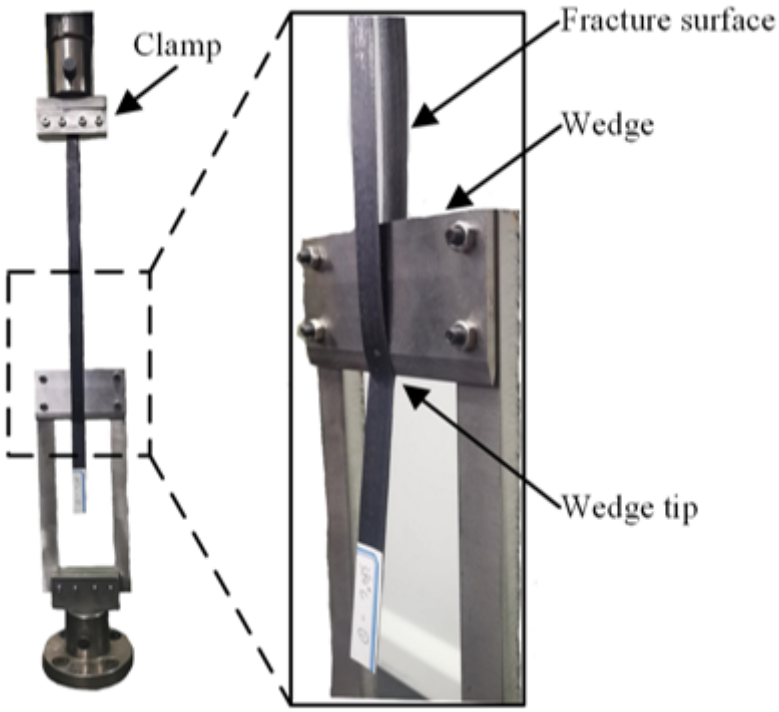

Figure 3

Image of the devised used for the wedge peel tests.

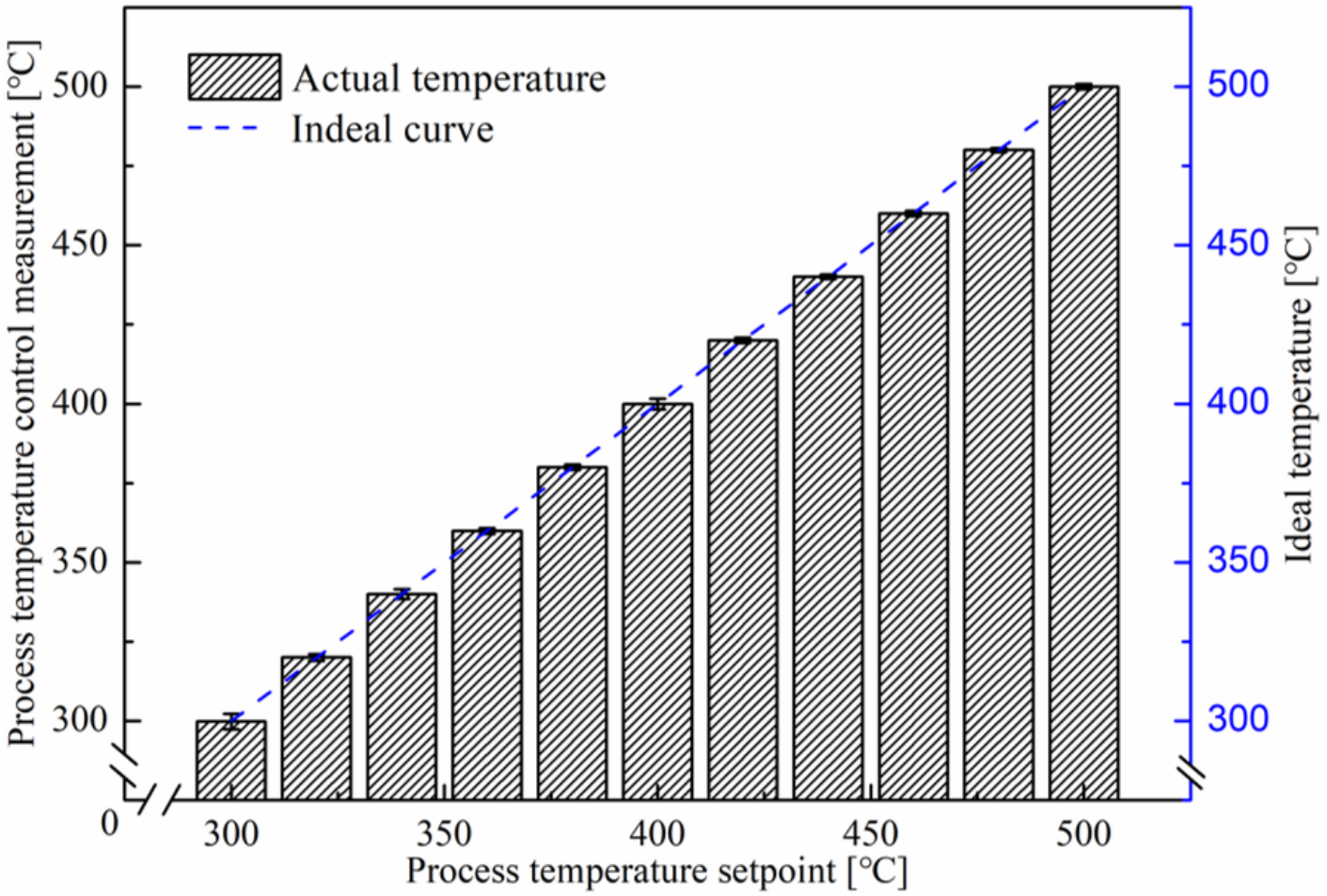

Figure 4

Average and standard deviation of the control temperature of the measurement process from the control setpoint.

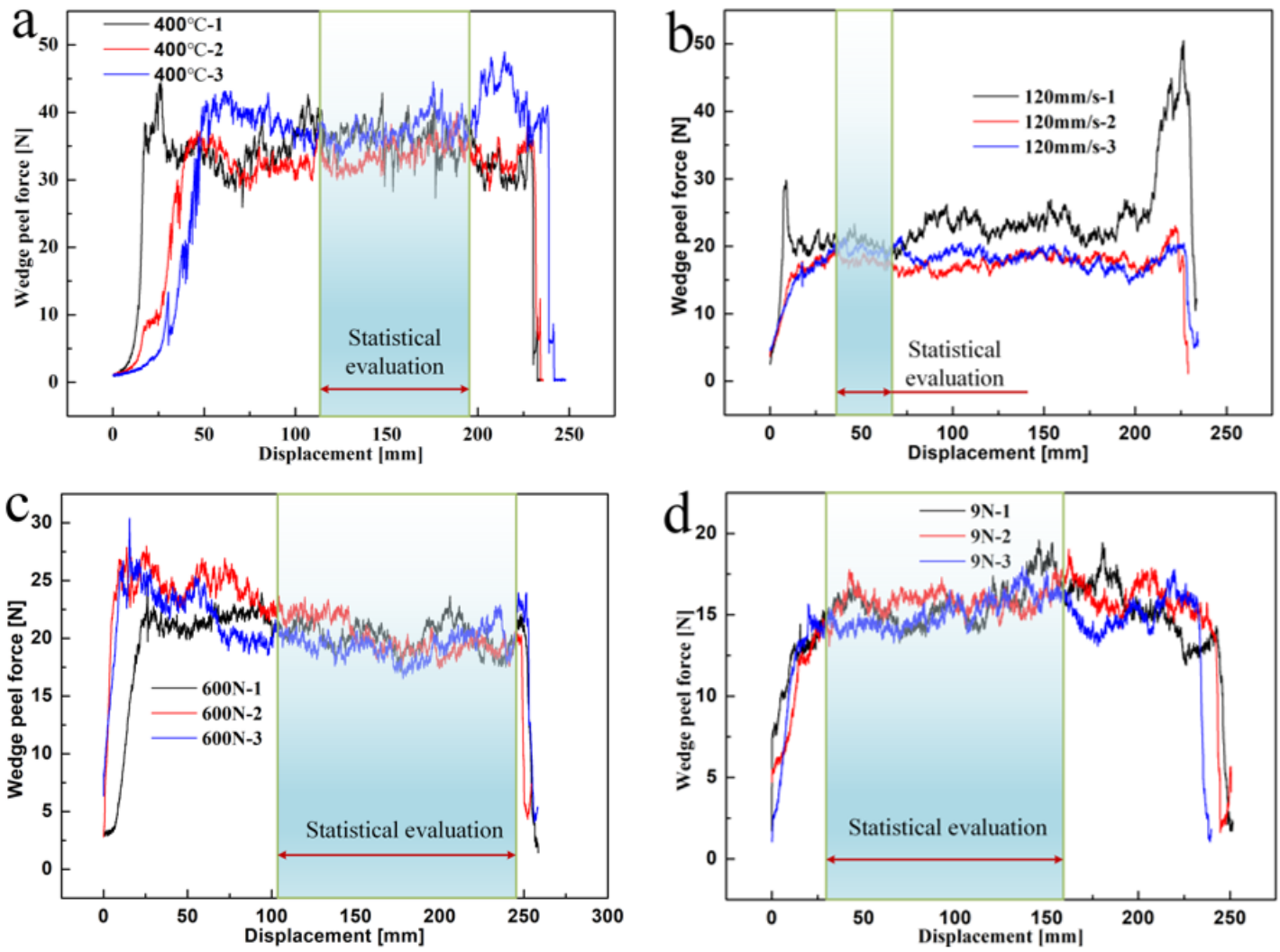

Figure 5

Typical force-displacement graphs for the wedge peel tests showing the region of data used for statistical evaluation of the sample prepared with different process parameters of (a) 400°C; (b) 120mm/s; (c) 600N; (d)9N.

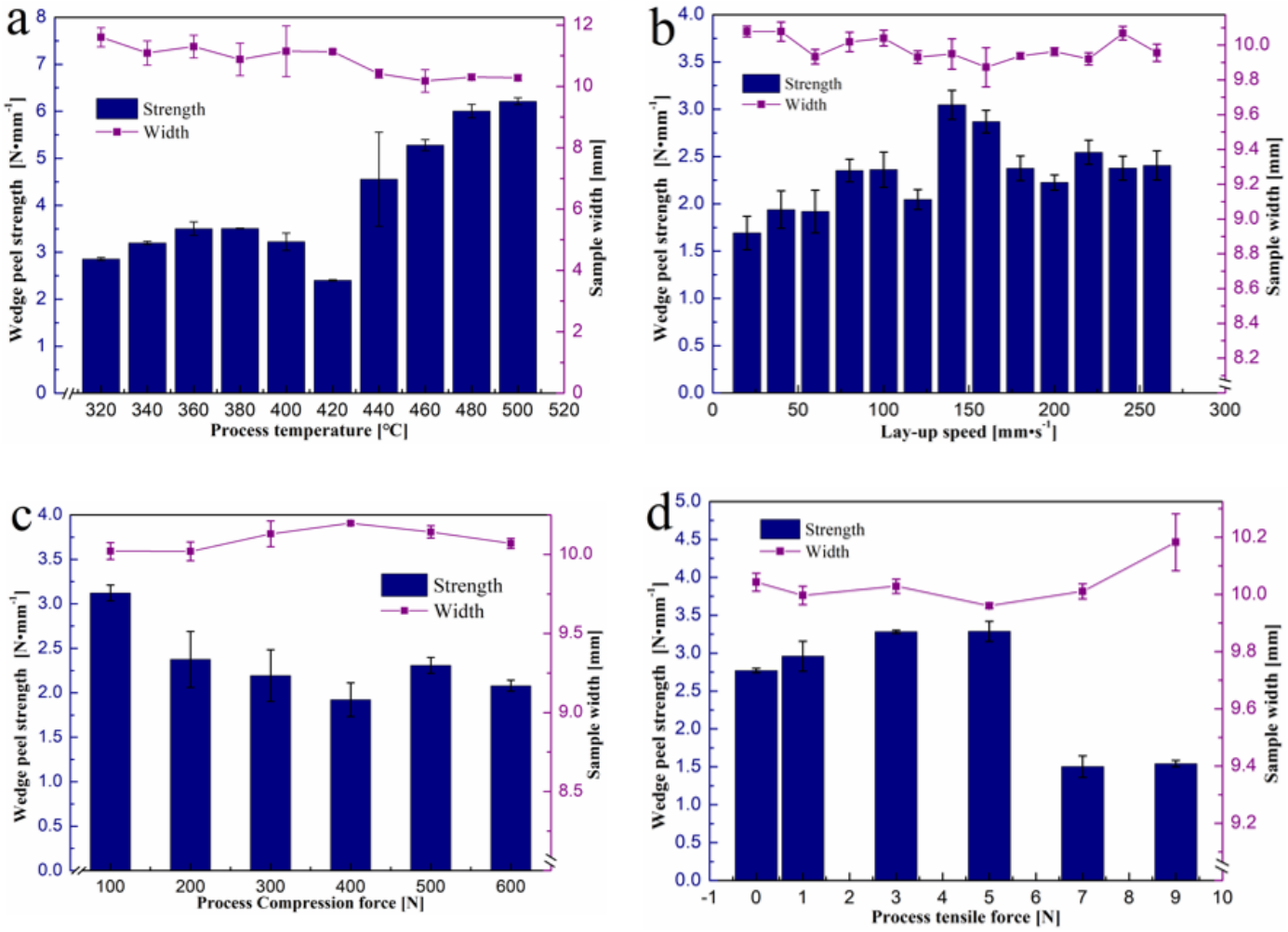

Figure 6

The effect of (a) process temperature, (b) lay-up speed, (c) process compression force and (d) process tensile force on the wedge peel strength of the resulting samples.

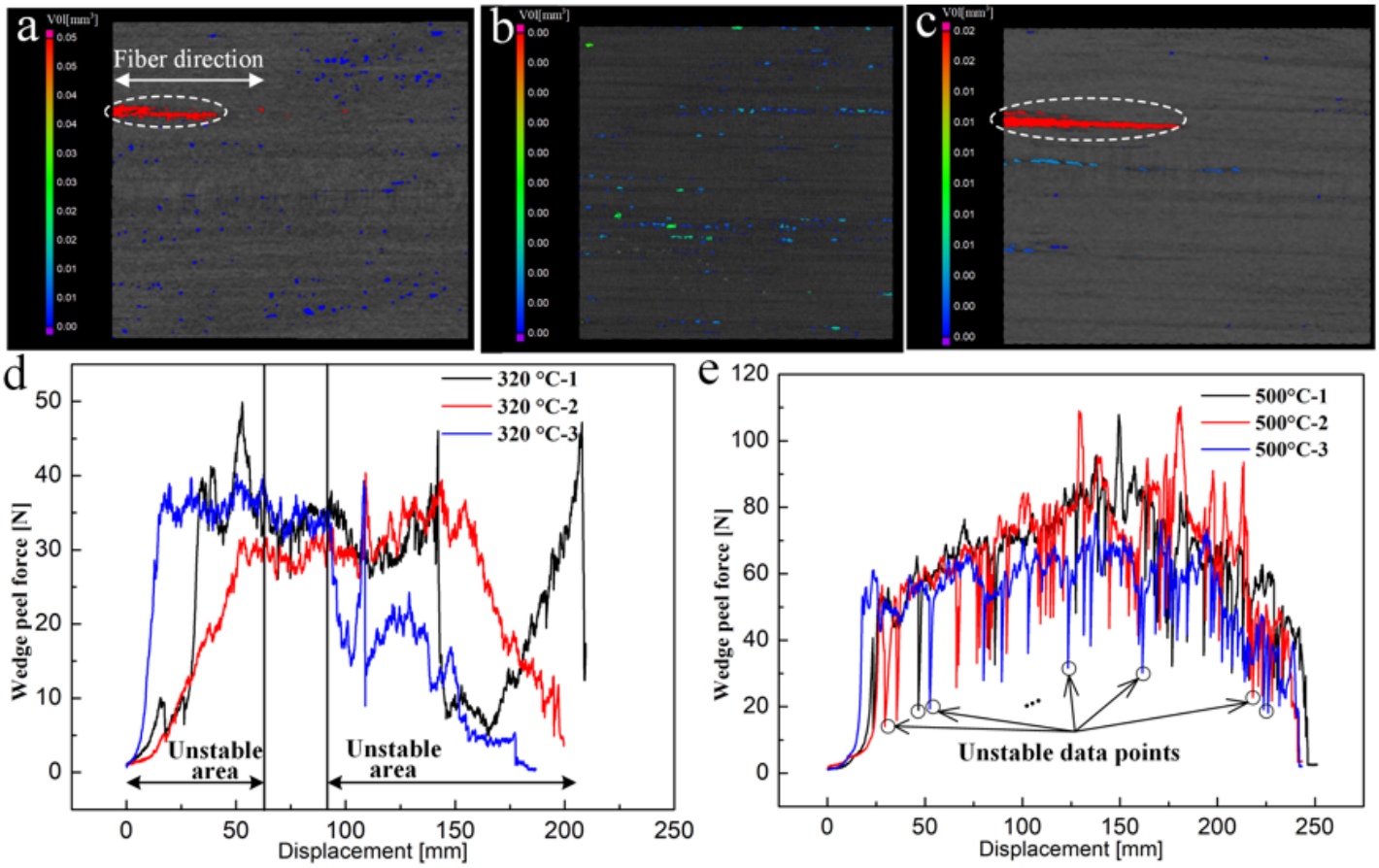

Figure 7

Pore size distributions of samples laid up at (a)320°C, (b)400°C, and (c)500°C, and force-displacement curves from the wedge peel tests of samples laid up at (d)320°C and (e)500°C.

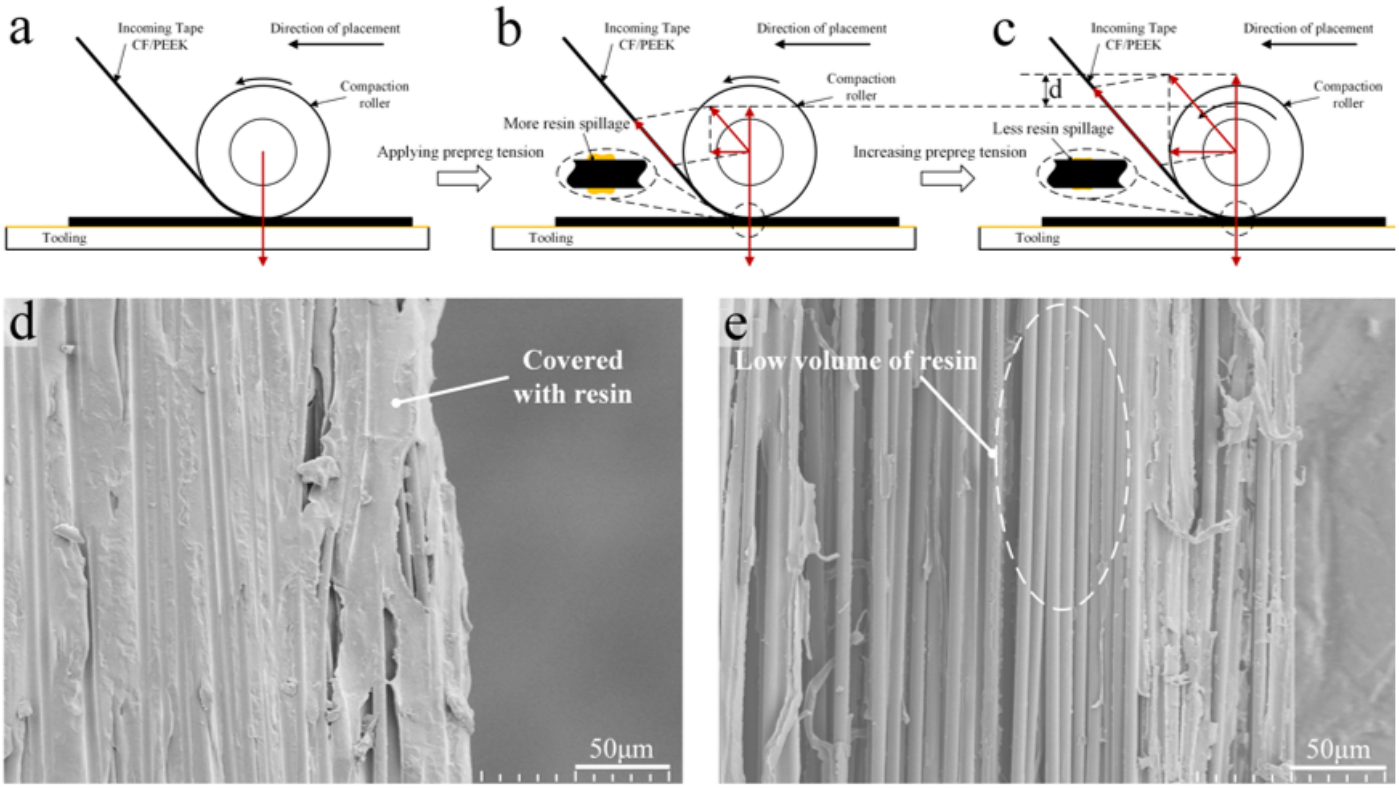

Figure 8

Illustration of sample preparation with (a) no prepreg tape tension, (b) low prepreg tape tension, and (c) high prepreg tape tension, and cross-sectional images of the wedge test damage surface in samples prepared with (d) low prepreg tape tension and (e) high prepreg tape tension.

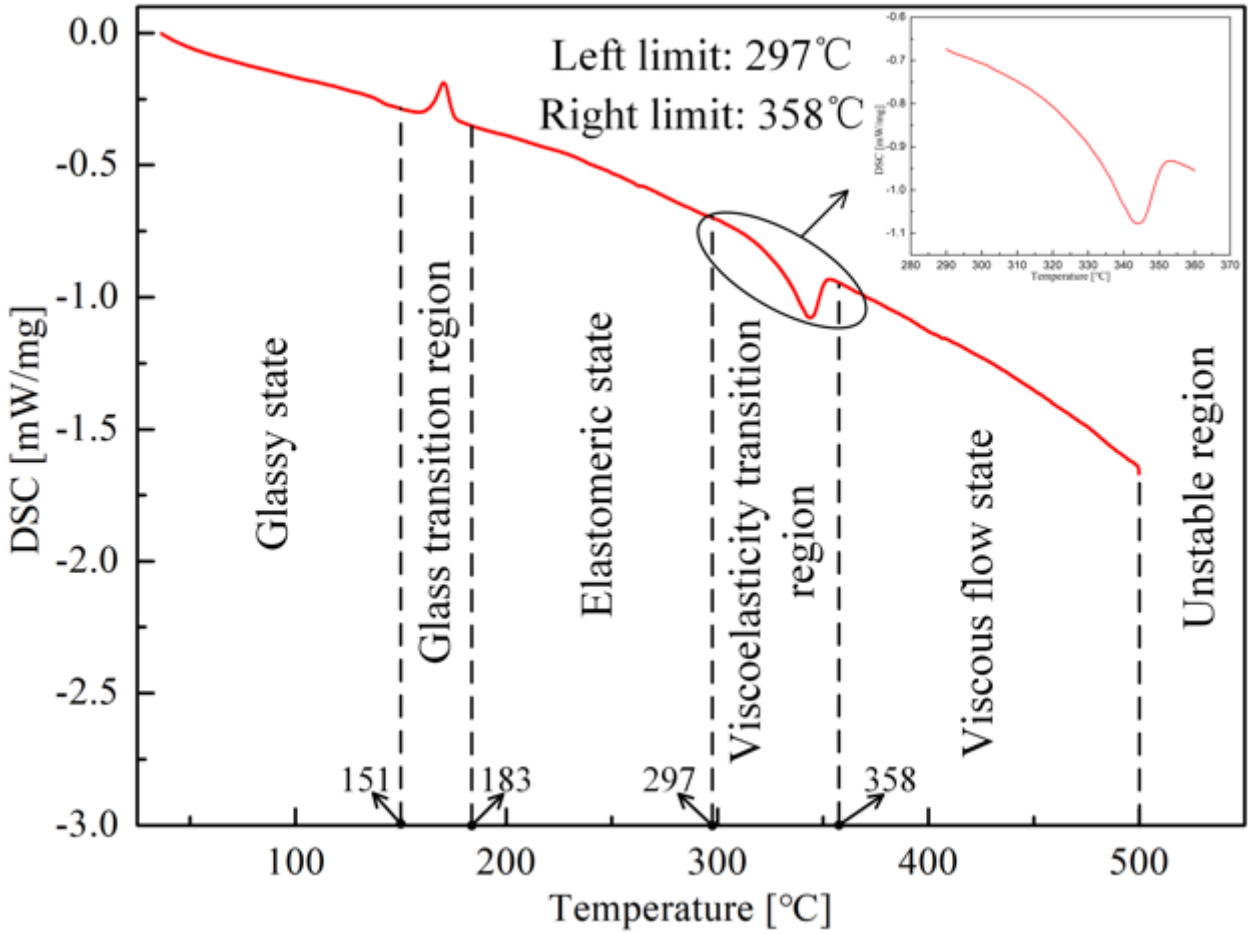

Figure 9

Typical DSC thermogram of the CF/PEEK prepreg.

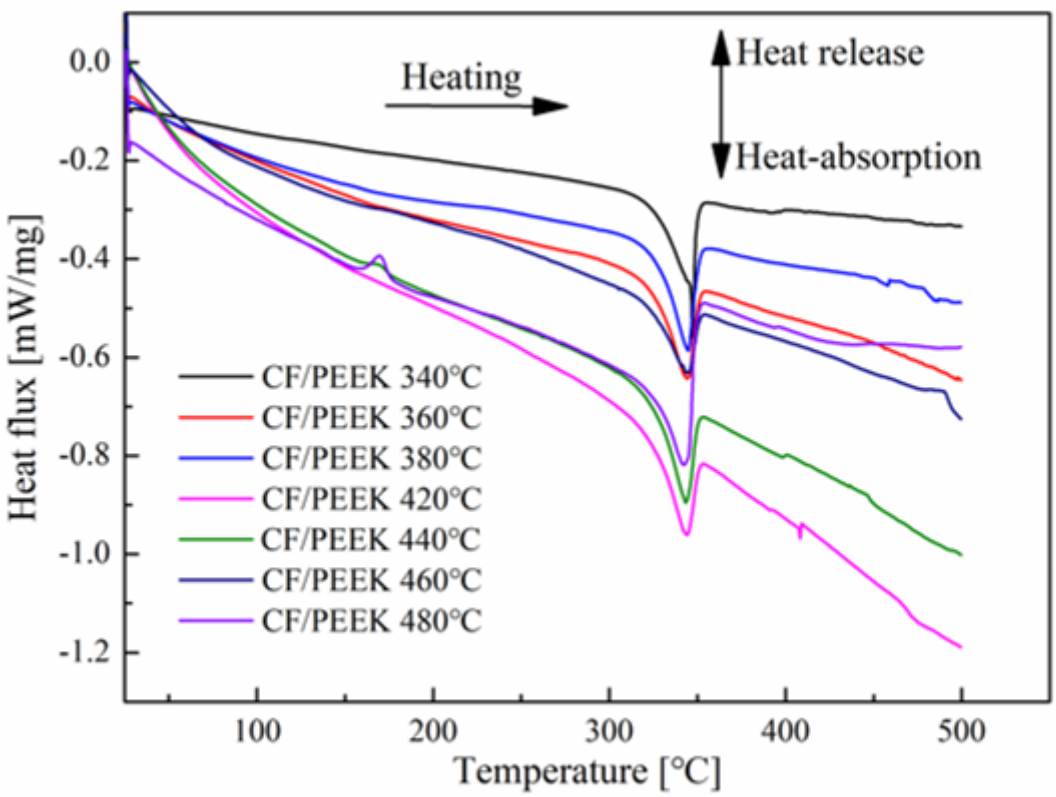

Figure 10

DSC curves measure of samples laid up at different temperatures.

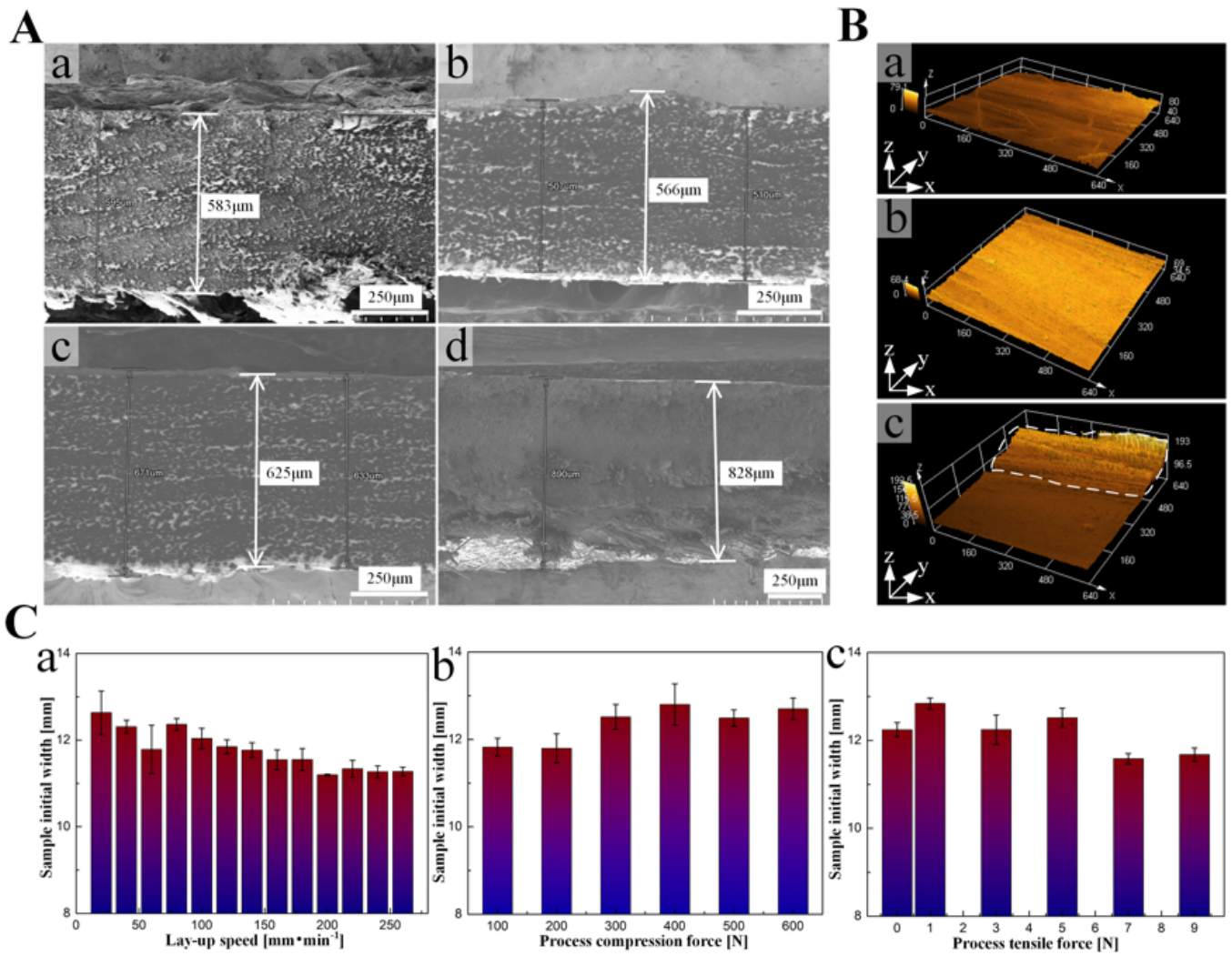

Figure 11

Cross-sectional images of the sample microstructure prepared with prepreg tape tension of A(a) 1 N, A(b) 3 N, A(c) 5 N, and A(d) 9 N, warpage and deformation of the samples prepared at irradiation temperatures of B(a) 320 °C, B(b) 400 °C, and B(c) 500 °C, and effect of C different lay-up parameters on the width of the original samples.