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Robotic Automated Fiber Placement of carbon fiber towpregs

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Robotic Automated Fiber Placement of carbon fiber towpregs

Robotic Automated Fiber Placement (R-AFP) technology was developed to manufacture composite laminates by placing carbon fiber thermoset towpregs, obtained by impregnating 12K high-strength grade carbon fibers in an epoxy resin system. In order to avoid placement induced defects, a thermographic scanning technique was implemented for on-line quality monitoring of the R-AFP process. The thermal analysis proved to be an effective and quick approach for the real-time detection of deposition defects generated during. The R-AFP process was performed by applying a constant pressure through the compaction roller; different pressure values were investigated. The effect of the resin weight fraction and compaction pressure on the mechanical properties applied by the deposition head during R-AFP of cross-ply laminates was studied. The reduction of the tensile strength and the increase of the elastic modulus with decreasing pressure of the compaction roller was observed. Furthermore, the values of ultimate tensile strength and elastic modulus decrease as the resin content increases. Finally, the three-dimensional topography of surface fracture of tensile samples was investigated by means of the optical and scanning electron microscopy.

Keywords: Carbon fiber reinforced polymer; towpreg; robotic automated fiber placement; thermographic scanning technique; on-line quality monitoring; scanning electron microscopy; compaction pressure control; resin weight fraction; optical microscopy; fracture surface; induced deposition defect, mechanical properties; tensile strength; modulus.

1 Introduction

Composite materials are well known for their extraordinary characteristics in terms of specific mechanical performances, especially as continuous carbon fibers are used as reinforcement. CFRP (Carbon Fiber Reinforced Polymers) exhibits a constant growth in applications where lightness and resistance are the main objectives to be fulfilled [1]. Manufacturing techniques for producing CFRP are mainly based on the addition of preimpregnated layers until the desired laminate thickness is obtained. The lay-up process can be performed manually or by means of automated systems. In the former, operators realize the stacking of preimpregnated layers over a mould which is then placed in an oven or in an autoclave for matrix polymerization. Manual methods are typically associated to long manufacturing times and high costs, highly skilled operators and low repeatability. To overcome these drawbacks, automated processes have been developed in order to perform material lay-up with lower costs, higher productivity and repeatability with respect to manual processes [2]. The most used automated methods to produce CFRP components are Filament Winding (FW), automated tape laying (ATL) and automated fiber placement (AFP). The latter is gaining great interest in the scientific and industrial communities and can be performed by mounting the deposition head on a robotic arm (R-AFP) in order to obtain higher freedom of movement which allows to realize more complex shapes [3]. In the Robotic-AFP (R-AFP) process a preimpregnated fiber tows, named towpregs, are pulled into a fiber delivery system under controlled tension where they are collected into a thin band to produce complex shapes with concave and convex surfaces. The fiber placement head is the end effector of a robotic arm which moves the deposition head to place towpregs on a mould surface with a compaction roller. A heating source, mounted on the fiber placement head, is used to increase towpreg temperature enhancing its tack and reducing detachments and deposition issues [4].

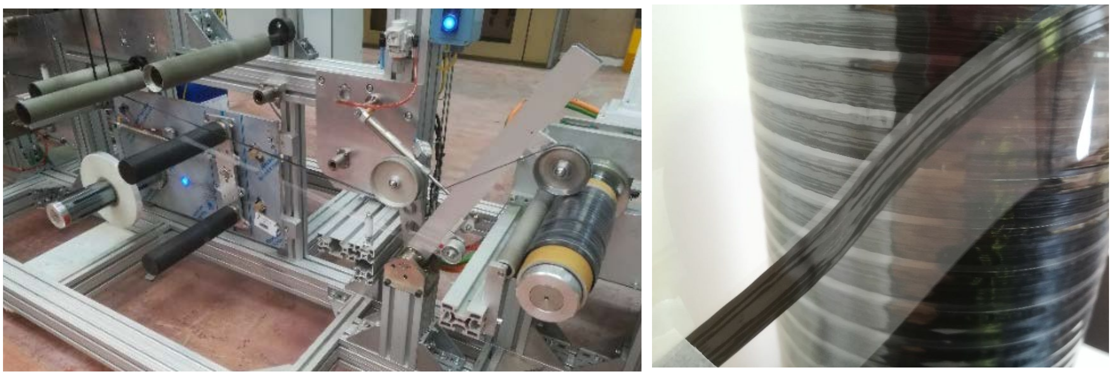
A critical aspect of the R-AFP system is the control of the compaction pressure applied during the lay-up process. Indeed, the consolidation of the material stack strongly depends on the force generated by the compaction roller. Insufficient compaction pressure can result in air entrapment and low interlaminar adhesion. On the other hand, an excess of compaction pressure can result in fibers damage and non-uniform resin distribution [5,6]. Other defects typical of CFRP components manufactured through R-AFP deposition systems are the occurrence of gaps between collimating tows, overlaps of adjacent tows and twisted tows [7,8]. These defects can cause premature failure during the part service life and different attempts to optimize deposition process have been found in literature [9–12]. Different methods have been developed for the in-situ control of the deposition phase [13]. Among them, thermography is one of the most performing due to their non-contact and non-destructive analysis capabilities. Defects can be identified during the deposition process by analysing the temperature of the towpreg which can result colder or hotter than the substrate as twisted tows and overlaps or gaps occur, respectively. Different studies demonstrated the capability to identify deposition defects using a thermal camera [14–16]. In addition, thermography can be also used to identify deposition errors on the cured laminates, as demonstrated by Elsherbini et al. [17], Sun et al. [18] and Pei et al. [19].

In the state of the art there is a lack of comprehensive studies concerning the in-situ control of the deposition phase and the effect of compaction pressure on CFRP laminates mechanical properties. For this reason, the aim of this work is to demonstrate the capability of thermography to identify gaps, overlaps and twisted tows and to correlate the effect of compaction pressure on mechanical properties of CFRP laminates. To this purpose, a thermal camera was used to analyse the deposition process of towpregs in which defects (gaps, overlaps, twisted tows) were intentionally induced. Furthermore, towpregs with different resin weight fraction (RWF) values, were used to realize CFRP laminates through R-AFP and the effects of compaction pressure on tensile strength and Young's modulus were investigated. Finally, the deposition defects and fracture surfaces of the tested samples were investigated using optical and scanning electron microscopies.

2 Material and Methods

2.1 Material and automated impregnation process

A 5-mm wide 12K high-strength carbon fiber tow, produced using polyacrylonitrile (PAN) as precursor, was impregnated by means of an epoxy resin system designed for autoclave curing. The impregnation process was performed using an automated fiber impregnation machine, developed by COMEC Innovative srl (Figure 1) [20].



(a) (b)

Figure 1. (a) Automated fiber impregnation machine and (b) towpreg spool after wrapping.

The epoxy resin was kept in a resistance oven at 60°C for 8 h in order to promote a homogeneous heating. Then, a constant quantity of the thermoset resin was applied on the tensioned dry tow using a spreader roll in order to control the unwinding and winding tension of 15 N and to ensure the quality of impregnation. An accurate control of the resin weight fraction (RWF) was carried out since RWF represents a key factor to ensure both accuracy of the deposition process and obtaining of the desired mechanical properties of composite laminate [21]. Figure 2 shows the homogeneous impregnation of the tow after the automated process.

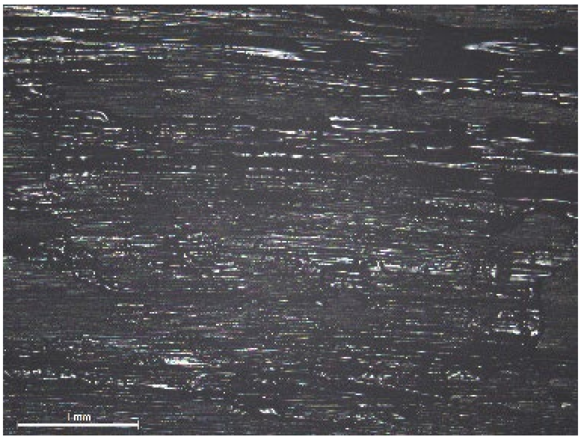
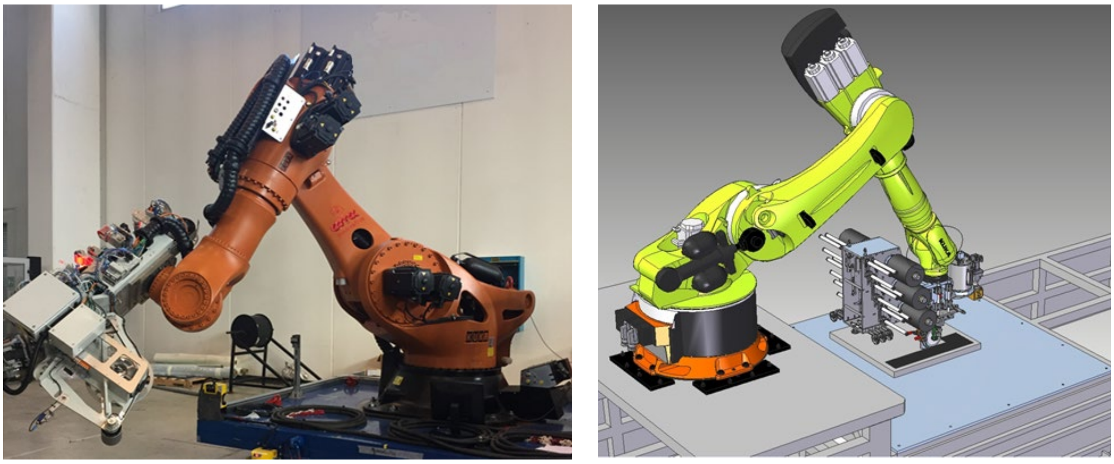


Figure 2. Magnification of carbon fiber tow after automated impregnation process (RWF=32%).

The impregnation process was performed with a tow speed equal to 20 m/min. The resin weight fraction (RWF) was kept constant during impregnation; different RWF values ranging from 25.1 to 35.9% were investigated. The RWF was measured by means of the resin digestion test performed according to the ASTM D3171 standard. A release paper in polypropylene was applied on the towpreg during wrapping in order to avoid adhesion between adjacent layers (Figure 1b). A refrigerated cabinet was used to store the towpregs spools after impregnation to avoid complete resin polymerization.

2.2 Robotic automated fiber placement process of towpregs

The towpreg deposition process was performed using a robotic automated fiber placement (R-AFP) system developed by Comec Innovative srl (Figure 3). The impregnated tows, taken from the refrigerated cabinet, were stored in the deposition head; they were fed through a series of guiding rollers and tensioners before deposition, ensuring that each towpreg followed a proper path to avoid their entanglement. The deposition head was manipulated by the KUKA KR 360 R2830 F six-degree-of-freedom robot characterized by a maximum payload of 472 kg, a pose repeatability of ±0.08 mm (ISO 9283) and a maximum reach of 2826 mm. The fiber placement device is able to ensure the correct orientation and positioning of towpregs. Furthermore, the system allows the towpreg cutting at the end of each deposition travel.



(a) (b)

Figure 3. (a) Robot used in the experimental work, and (b) computer-aided design of the Robotic automated fiber placement system.

A force sensor was used to measure the compaction force applied on the towpreg during the R-AFP process. The deposition experiments were performed by applying a constant pressure (p) through the compaction roller. In order to investigate the effect of the compaction force on the laminate properties, three different pressure values, varying in the range from 0.8 to 2.4 bar, were investigated.

The deposition speed was equal to 100 mm/s in order to maximize productivity. In order to increase the tack level, towpregs were heated before deposition lay-up with a heating system placed in the deposition head.

The R-AFP was used to produce cross-ply laminates [0°-90°] by stacking 20 layers. Each layer was obtained by laying-up unidirectional towpregs (Figure 4); the 0° layer was alternatively stacked with 90° one until reaching the desired number of plies. Composite panels were 300 mm in length and 300 mm in width, with different thickness values depending on the RWF value. After robotic lay-up, panles were cured in autoclave at 130°C for 2 h, with a pressure of 4 bars, according to the matrix datasheet.

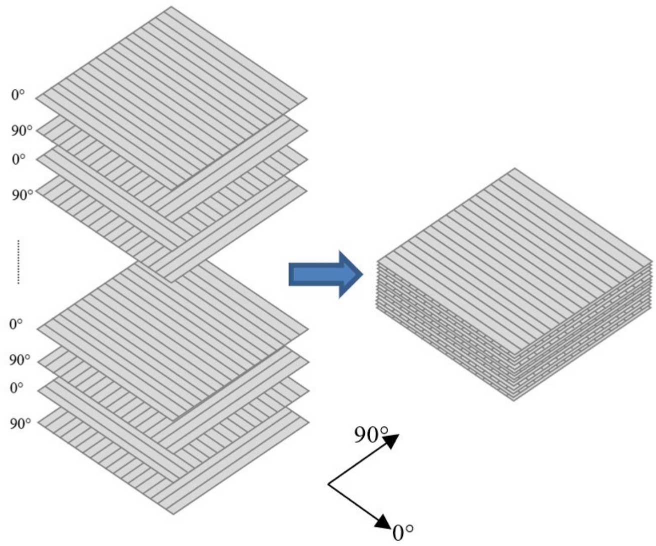


Figure 4. Scheme of the cross-ply laminate [0°-90°].

2.3 Thermographic scanning technique

The InfraTec VarioCAM® HD high-resolution thermographic system was used for the on-line monitoring of defects taking place during towpreg deposition. A maximum frame rate of 240 Hz allows an accurate recognition of extremely rapid temperature changes. The thermographic system is equipped with standard lens, a focal length of 30 mm and a field of view of 35x25°. The use of these lens represents an excellent tool to frame medium-sized parts within which it is necessary to detect defects of the order of magnitude of a millimeter or less.

The system capability to detect the typical defects taking place during automated deposition, such as gap, overlap and twisted tows, by analysing the temperature discrepancy between towpregs, was tested by programming the fiber deposition head to intentionally introduce defects.

2.4 Uniaxial tensile tests

The mechanical properties of consolidated laminates were evaluated by tensile tests, according to the ASTM D3039, carried out using the MTS 810® servo-hydraulic testing machine at a loading rate of 2 mm/min. Tensile specimens were obtained from the cured laminates by means of waterjet cutting operations; tensile tests were carried out both with loading direction coincident with the 0° deposition direction (type //0°) and 90° one (type //90°). In order to limit stress concentrations that can be caused by the clamping system of testing machine and to avoid premature failure, aluminium tabs, with a thickness of 2 mm, were bonded to each end of the specimen using a two-component epoxy adhesive. For each test condition, at least five specimens were tested.

2.5 Optical and scanning electron microscopies

In order to evaluate the effect of resin content, compaction pressure and the presence of defects induced during deposition, the cross-sections of CFRP panels were observed using the optical microscope Leica DMi8. Furthermore, the Leica Microsystems EZ4 Stereomicroscope was used to obtain macroscopic images of the fractured surface and longitudinal section of laminates after tensile tests. Finally, the scanning electron microscope (SEM) Fesem Zeiss Supra 40 at 10 kV was used to achieve high resolution images of the three-dimensional topography of the fractured surface of the laminates.

3. Results and Discussion

The capability of the thermal image-based monitoring to detect defects occurring during the R-AFP process was evaluated. To this purpose, deposition defects were intentionally introduced during the robotic lay-up process of towpregs to obtain cross-ply laminates. As far as the gap between collimating towpregs is concerned, it can reduce the performances of CFRP laminate since represents an area of discontinuity and non-straightness of the carbon fibers. In addition, the presence of gap leads to the formation of resin pocket characterized by poor mechanical strength [16,22]. Figure 5a shows a thermal image of the R-AFP process during which a gap takes place. It can be seen a zone between two adjacent towpregs just deposited characterized by lower temperatures indicating a lack of towpreg in the layer under deposition. The presence of a gap also causes, as observed by Denkena et al. [15], bridging tows since there is no connection between the towpregs and underlying layer. Such defect leads to a decrease in the heat conduction and the towpregs are colder. The optical microscopy of the cross-section of the CFRP laminate confirms the presence of gap between adjacent towpregs (Figure 6a). The gap, whose width is approximately 1 mm, affects the straightness of the layers laid-up above and below the defect, creating a distortion of the fibers. Such drawback results in a decrease in the mechanical performances of the laminate composite.

A further deposition defect induced by modifying the path of the robotic deposition head was the overlap between towpregs which causes a non-uniformity in the laminate thickness, in addition to the non-straightness of fibers. Figure 5b shows the thermal image of the automated fiber placement process with overlap formation. It can be seen a hot region indicating the towpreg superimposition in the layer under deposition. The occurrence of overlaps also leads to the presence of gaps due to the shift of the fibers towards different directions with respect to the ones of adjacent towpregs [16,22]. The optical microscopy carried out in the cross-section of laminate with the presence of overlaps shows an area in which the presence of two superimposed towpregs laid-up with the same fiber orientation can be observed (Figure 6b).

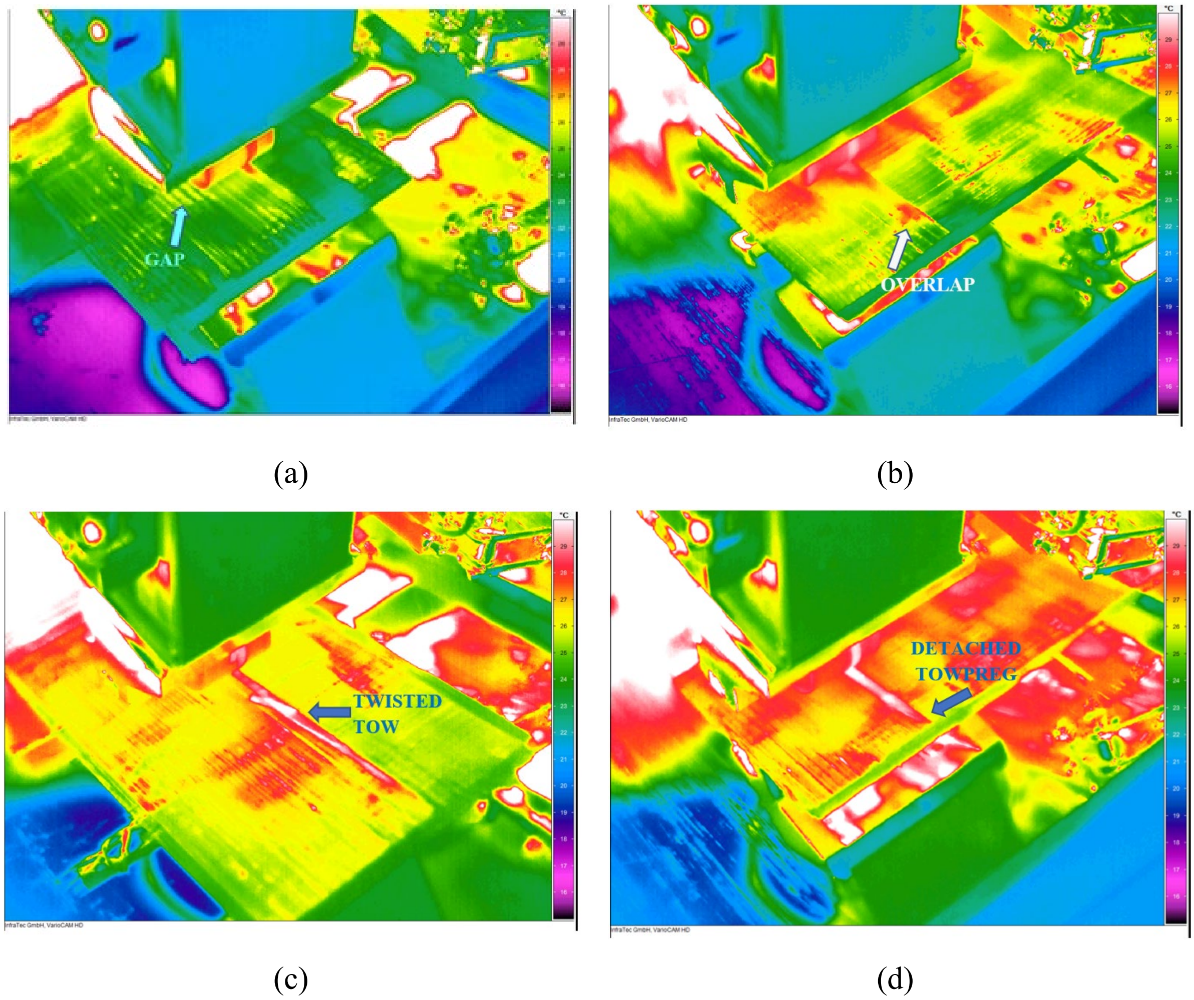


Figure 5. Thermal images of occurring defects during robotic automated fiber placement process: (a) gap and (b) overlap between towpregs, (c) twisted tow and (d) detached towpreg.

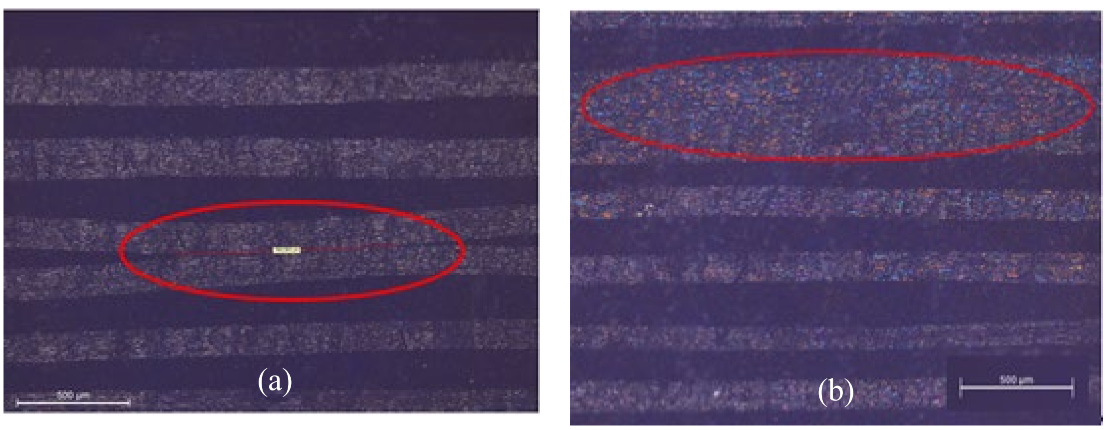


Figure 6. Optical microscopy of the cross-section of defective laminates due to the presence of: (a) gap and (b) overlap between towpregs.

Also twisted tows were introduced during R-AFP. This defect leads to a worsening in the performance of the CFRP laminate due to the non-straight arrangement of the fibers and the non-uniformity of the composite. The twisted tow influences both the layer on which it occurs, and the overlying ones due to the irregularity of the thickness [16]. Figure 5c shows the thermal image acquired during the R-AFP process with formation of twisted tows. Thermography detects an elongated shaped area, along the deposition direction, characterized by temperatures higher than those acquired in the defect-free zones.

The thermographic analysis also allows to detect the detachment of towpregs from the underlying layer, in particular near the laminate edges. Such defect can occur due to the low tack level of towpreg. The thermographic analysis shows a hot zone resulting in a sharp shape recorded by the thermal image. Furthermore, this behavior is even more evident as temperature decreases due to the cooling of towpreg.

Finally, Figure 7a shows a thermal image of a defect-free laid-up layer by the fiber deposition head. It can be observed the homogeneous temperature distribution on the surface of the laminate, indicating an almost uniform cooling of towpregs. The cross-section of a defect-free composite laminate, observed through the optical microscopy technique, shows that the cross-ply CFRP laminate is homogeneous, and the individual layers have been uniformly deposited (Figure 7b).

The results obtained by the in-situ thermal image-based monitoring system during R-AFP process indicate that the thermal analysis is an effective and quick approach for the real-time detection of the defects generated during the robotic deposition. For this reason, the thermographic analysis system can significantly reduce the efforts in the quality control and assure the steady quality assurance in composite structure manufacturing.

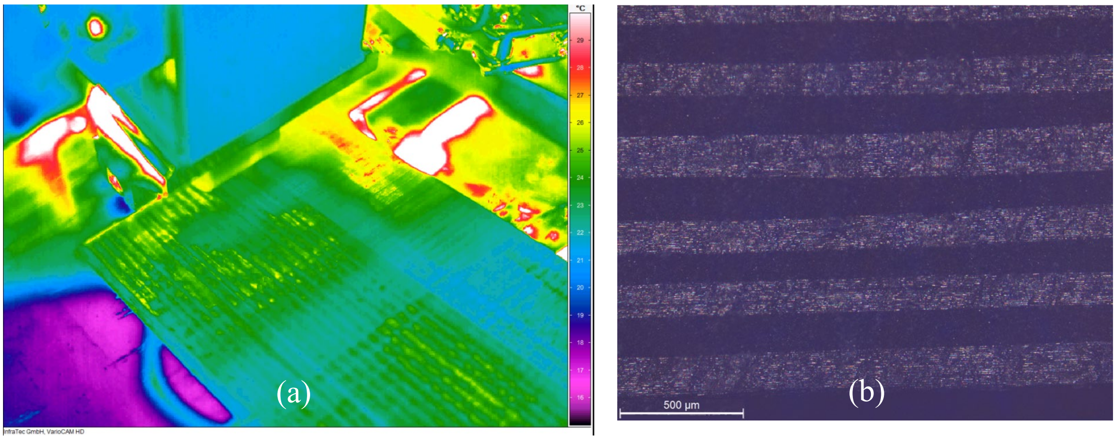
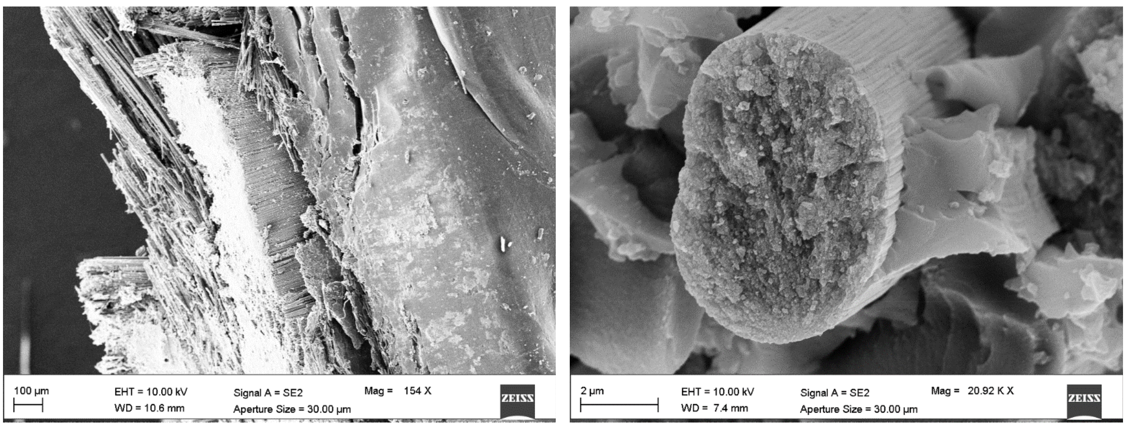


Figure 7. (a) Thermal image and (b) optical microscopy of the cross-section of defect-free composite laminate.

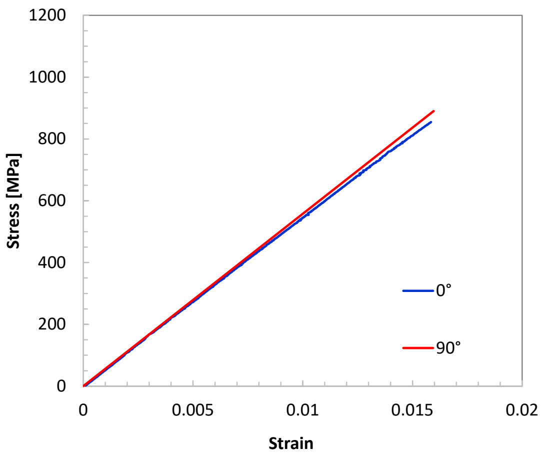
The mechanical properties of consolidated cross-ply laminates, in terms of ultimate tensile strength, elastic modulus and fracture behaviour, were evaluated by means of uniaxial tensile tests. A typical SEM three-dimensional topography of the fractured surface of the CFRP composite laminate is shown in Figure 8a, in which the cross-ply structure can be observed. Figure 8b shows a magnification of a CFRP tow impregnated with epoxy resin.



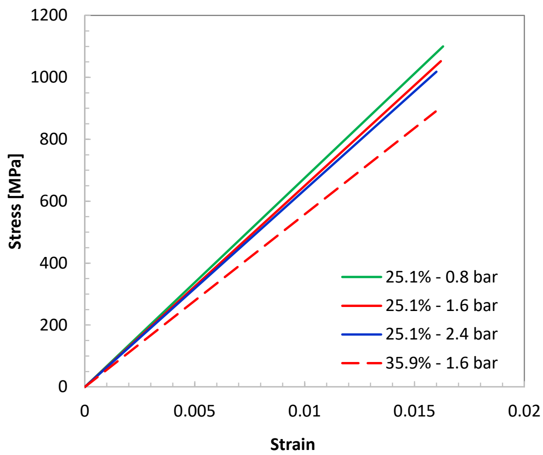
(a) (b)

Figure 8. (a) Typical three-dimensional topography of the fractured surface of the cross-ply laminate obtained using scanning electron microscopy and (b) carbon fiber tow.

Figure 9 shows typical stress - strain curves obtained by tensile tests on CFRP laminates after curing. Specifically, in Figure 9a stress vs. strain curves of samples with axis coincident with both 0° and 90° deposition directions are plotted. No significant effect of the loading direction appears. Irrespective of process parameters, the s-e curves exhibit a linear elastic behaviour, also in the larger displacement region until fracture, according to the results reported by Woigk et al. [23]. In Figure 9b typical s-e curves given by samples characterized by different RWF and p values are shown. For a given strain level, an increase in both resin content and compaction pressure applied during robotic deposition leads to a decrease in strength and stiffness.



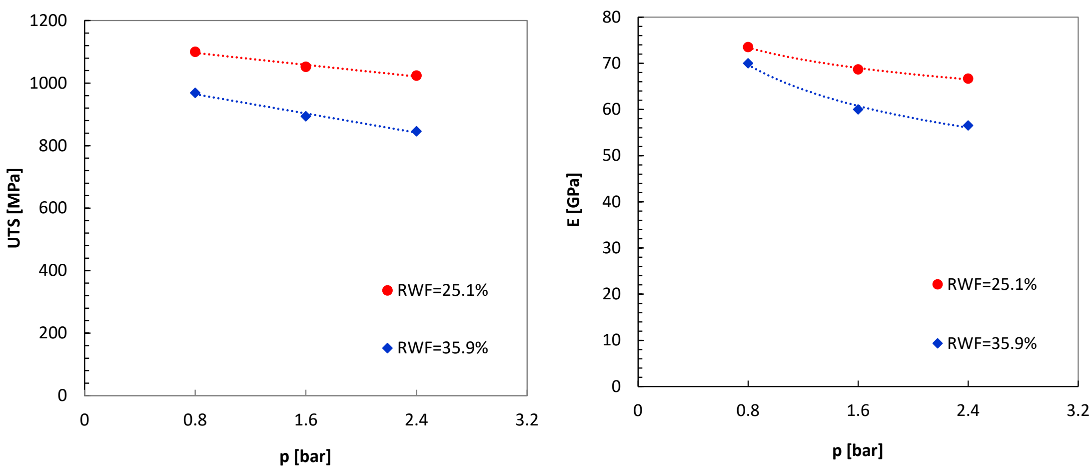
(a)



(b)

Figure 9. Effect of (a) loading direction (RWF=35.9%, p=1.6 bar), and (b) resin weight fraction and compaction pressure on typical stress-strain curves obtained by tensile tests performed on samples in CFRP laminates after curing.

Figure 10 shows the mean values of ultimate tensile strength and elastic modulus for each testing condition investigated. As far as the influence of compaction pressure is concerned, irrespective of RWF, a decrease both in UTS and E values with increasing pressure from 0.8 to 2.4 bar can be seen. Such result can be related to the compression load applied by the compaction roller on the carbon fibers lay-up by the robotic deposition head. As a matter of fact, the increase in the p value leads to higher stresses acting perpendicularly to the fiber axis and, as shown in Figure 11, can cause the occurrence of transverse failure of carbon fibers, leading to increasingly poor mechanical properties. Such evidence demonstrates as an appropriate compaction pressure applied during R-AFP process is fundamental to avoid fiber fractures, according to the results shown by Bendemra et al. [24], Aized and Shirinzadeh [9] and Venkatesan et al. [25].



(a) (b)

Figure 10. Effect of the resin weight fraction and compaction pressure applied during R-AFP of composite laminates on results given by tensile tests: (a) ultimate tensile strength and (b) elastic modulus.

As far as the influence of resin content on elastic modulus and ultimate tensile strength is concerned, Figure 10 shows that a decrease in RWF leads to a significant increase in both UTS and E values due to the increase in the reinforcement content.

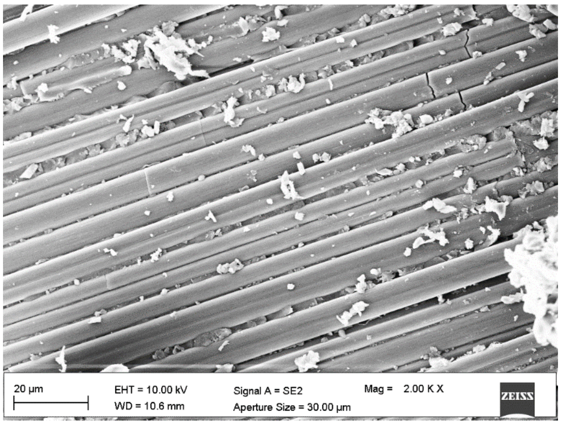
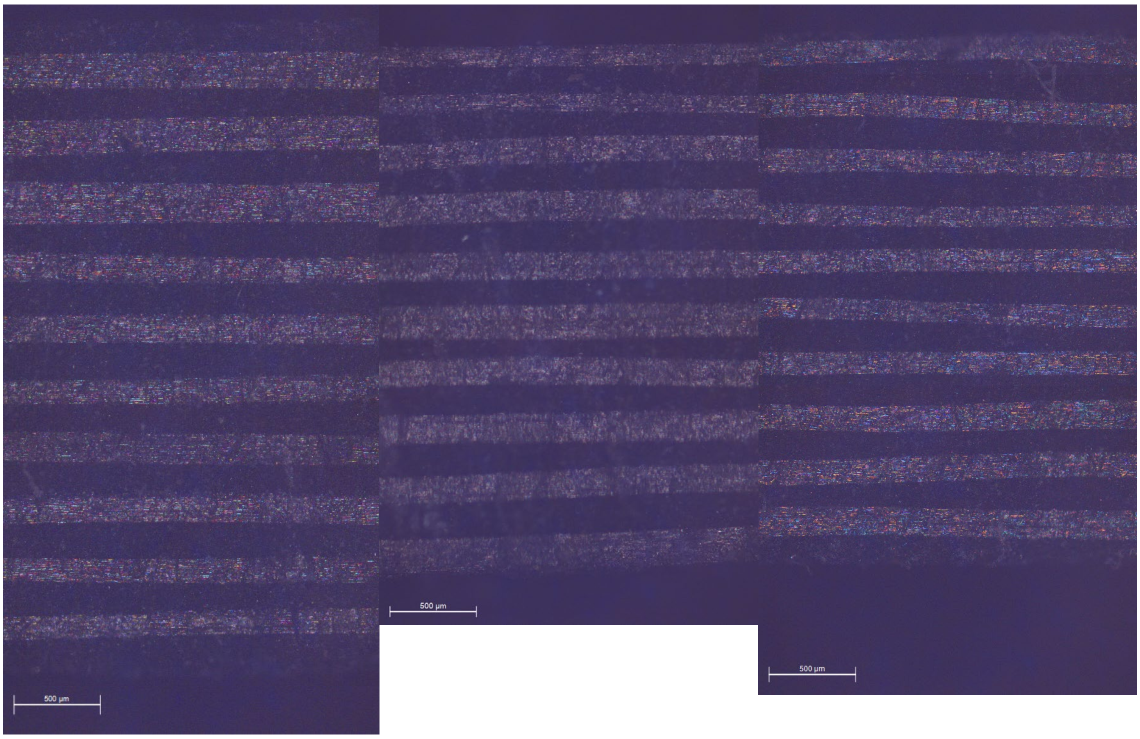


Figure 11. Scanning electron microscopy of top surface of CFRP laminates after curing (RWF = 35.9%, p=2.4 bar).

Figures 12a and 12b show as, for a given compaction pressure and number of layers, the reduction in resin content from 35.9 to 25.1% leads to a decrease in the laminate thickness from 3.9 to 3.2 mm. Furthermore, Figures 12b and 12c shows as, for a given RWF value and number of layers, an increase in p value from 1.6 to 2.4 bar leads to a decrease in laminate thickness from 3.2 to 3.1 mm.



(a) (b) (c)

Figure 12. Cross-section of the composite laminate observed under an optical microscope: (a) RWF = 35.9% (pressure = 1.6 bar); (b) RWF = 25.1% (pressure = 1.6 bar); (c) RWF = 25.1% (pressure = 2.4 bar).

In cross-ply laminates, failure begins with transverse microcracks appearing in 90° plies. As the stress level further increases, the number of transverse microcracks increases until saturation is reached. Delamination, fiber failure and longitudinal cracking can follow transverse crack formation. In the present investigation, after transverse microcraking, a marked delamination between layers appears as the RWF is equal to 25.1% (Figure 13a). Such behaviour can be attributed to the low quantity of resin between the towpreg layers, that is insufficient to guarantee adhesion between layers as tensile stress approaches the strength to failure of the composite laminate. The delamination can occur on several adjacent layers and, therefore, the debonding surface can appear as a flat stepped surface (Figure 14a). Therefore, even though the reduction in the resin content leads to an improvement in the mechanical properties of the composite laminate, it involves the specimen failure through the debonding of the layers due to the low quantity of resin matrix. As the RWF increases up to 35.9% (Figure 13b), the debonding mechanism is strongly reduced; transverse matrix cracks arise in the 90° plies because of their relatively low strength in the loading direction. At those matrix cracks, high interlaminar shear stresses develop and thus delamination occurs and propagates between ply interfaces (Figure 14b). Notwithstanding such damage mechanisms, the load bearing 0° plies were still undamaged and no load drop was observed, according to the stress – strain behaviour shown in Figure 9. As load further increases, fiber failure in 0° ply occurred, leading to the quick failure of specimen [23].

Conclusions

In the present work, the lay-up process of fiber carbon tows preimpregnated with a thermoset epoxy resin was investigated by means of a robotic automated fiber placement machine. The deposition process involves the lay-up of individual towpregs onto a flat mold in order to obtain cross-ply laminates. The effect of the resin weight fraction prior to cure and compaction pressure applied during deposition on the mechanical properties of consolidated laminate was investigated. An in-situ thermal image-based monitoring was implemented to detect the occurrence of defects during robotic deposition, for on-line quality control of the process.

The main results can be summarized as follows:

- typical stress-strain curve exhibits linear elastic material behaviour until failure;
- a decrease in the resin content impregnating the tow leads to a significant increase in both elastic modulus and ultimate tensile strength;
- thermal analysis proved to be an effective and quick approach for the real-time detection of the defects generated during the robotic deposition;
- an increase in compaction pressure applied during robotic lay-up process leads to a marked decrease in both ultimate tensile strength and elastic modulus due to the higher stresses acting perpendicularly to the carbon fiber axis, leading to the occurrence of transversal failure of fibers;
- low values of the resin weight fraction (RWF=25.1%) leads to the occurrence of debonding of surface layers, parallel to the loading direction;
- high values of the resin weight fraction (RWF=35.9%) causes the presence of transverse matrix cracks arising in the 90° plies and delamination between ply

interfaces. Notwithstanding such damage mechanisms, the load bearing 0° plies were still undamaged until fiber failure in 0° ply occurred.

Acknowledgements

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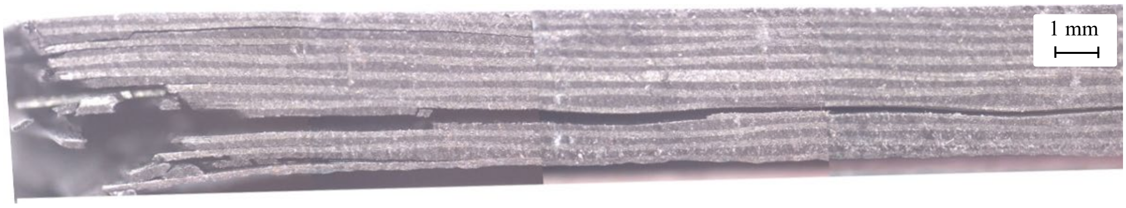
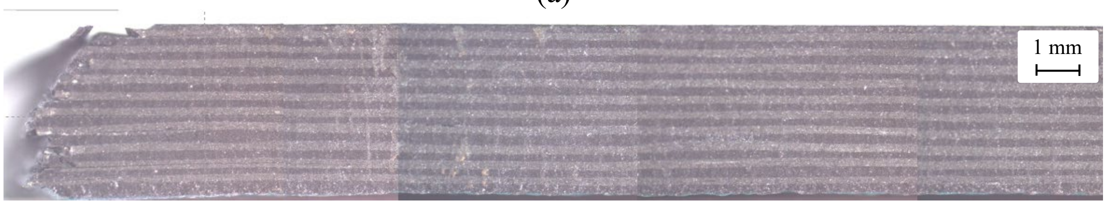
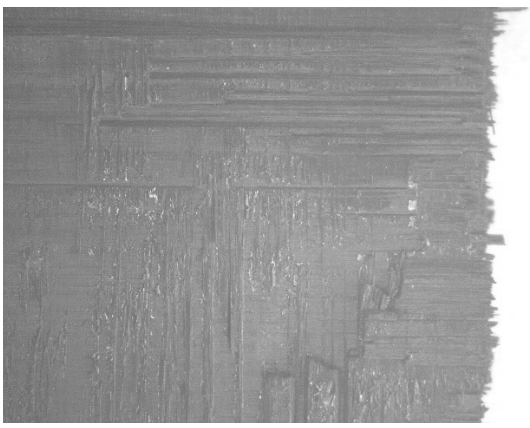


(a)



(b)

Figure 13. Effect of resin content on typical cross-section of fractured tensile specimens obtained laying up towpregs at different resin weight fractions: (a) RWF=25.1% and (b) RWF= 35.9% (p=1.6 bar).



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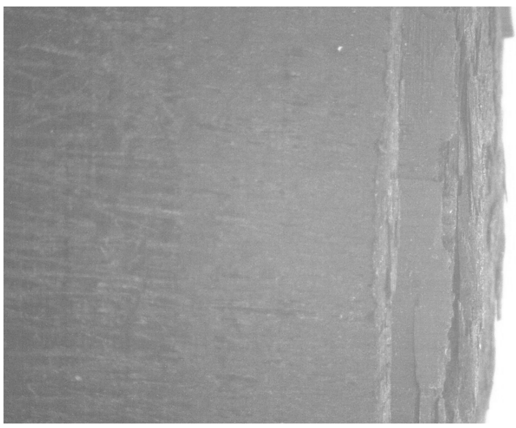

(b)

Figure 14. Typical fractured tensile specimens cut by laminates obtained laying up towpregs at different resin weight fractions: (a) top surface and (b) cross-section of sample at RWF=25.1%; (c) top surface and (d) cross-section of sample with RWF= 35.9% (p=1.6 bar).

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