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Some Experimental Investigation of Products from Thermoplastic Composite Materials Manufactured with Robot and LAFP

Samoil Samak, M.Sc[1], Svetlana Risteska, Ph. D[2], Vladimir Dukovski, Ph.D[3], Sase Trajkoski, Postgraduate student[1]
[1]Mikrosam D.O.O Krusevski pat bb -Prilep R. N. Macedonia
[2]Institute of Advanced Composites and Robotics-Prilep, R. N. Macedonia
[3]Faculty of Mechanical Engineering Ss. Cyril and Methodius University Skopje, R. N. Macedonia

Abstract:- **For successful avoiding of the irregularities and errors in the products from composite materials, it is important to manage the whole production process in real time. This applies to detecting certain irregularities (positioning defects, bonding defects), controlling the robot and process parameters.**

This paper presents results from an experimental study of the influence of embedded defects created during in - situ laser automated fiber tape placement (LAFP), on the mechanical properties of carbon/PEEK composites. Three rings have been examined with different designs [(0/±45˚)n], [(0/±30˚)n] and [(0/±90˚)n], in which gaps and overlaps have been introduced during fiber placement. The microstructures were characterized by optic microscopy. ILSS tests were performed on samples from rings and showed that the presence of a gap/overlap and voids more than 3% affect mechanical behavior of pipes but does not affect degree of crystallinity.

Keywords: LAFP; defects; process parametrs, ILSS, void

I. INTRUDUCTION

Composite material is a combination of two or more materials which results with improved properties in comparison to the properties of individual application of the same materials. Recently, the thermoplastic matrix composites are finding new applications in different industrial area due to their intrinsic advantages related to environmental compatibility and process-ability [1-4].

The quality of the final composite thermoplastic part depends mostly on machine (robot) accuracy, the geometry of the object where the laying is performed and process parameters.

Robot accuracy research has long been a focal point not only for scientific institutions, but even more so for companies that make robots and those that use them. Samak et al. [5] described the influence of the calibration of the robot on the accuracy of ATL/AFP process. Hallander et al. [6] evaluated the effect of the layup sequence, ply thickness and ply pre-compaction on the wrinkle occurrence when forming a quasi-isotropic laminate made of unidirectional layers. For a double curved geometry, their results showed that the layup sequence had a dominant effect compared to other parameters. Haanappel et al. [7,8] have shown clear differences in terms of ply wrinkling, between a unidirectional CF/PEEK and a carbon/polyphenylene-sulfide (CF/PPS) using a carbon fabric for the molding of complex part geometry. They observed that the UD material had more difficulties in conforming to 3D geometries, and they highlighted the fact that both types of composite cannot be deemed similar when considering the processing cycle. The challenge of automated fiber placement is to completely lay down the laminate with a defined fiber orientation without gaps or overlaps. Successful fiber placement without gaps or overlaps is dependent on many parameters, such as mold geometry, tape width, and fiber orientation. Study [9] has shown that the effect of overlaps can reduce in-plane shear strength (ILSS) by up to 13%. Overlapping is more important than the problem of gaps.

The void content of in-situ consolidated TPC parts depends on process parameters (the layup speed of fiber, temperature, part geometry and prepreg quality). Another key concern in-situ consolidated TPC part is crystallinity (the ordered molecular structure that forms in semi-crystalline polymers, such as PEEK, PEKK and PPS, as they cool from melt temperature to a solid). In general, slower cooling rates increase crystallinity, which results in higher mechanical properties and chemical resistance in the finished laminate [10-24]. Chen and Chung [10] studied the crystallization kinetics of CF/PEEK composites at 61% fiber volume content, for both the isothermal and the non-isothermal crystallization approaches. They showed that a higher cooling rate causes the crystallization to start at a lower temperature and is obtained over a wider temperature range.

Many authors [20-35] today work to improve the in - situ laser assisted AFP process. Some work [25] on intimate contact and heat transfer, some work [26-30] on fixing and removing defects that occur in the whole process and some work [30-35] on technological processes that require the appropriate technological parameters to improve product quality.

The present paper reports on studies for possible defects and process parameters during robotized LAFP process. One of the primary objectives of this phase of the study is to identify the dominant processing parameters and establish their influence on the quality of final composite materials.

II. LAFP PROCESS

The laser-assisted tape/fiber placement (LATP/LAFP) process is an automated composite manufacturing technique often quoted for its potential ability to produce composite parts with an in-situ consolidation, which avoids an expensive time and energy consuming step of post-consolidation. But, in order to be competitive this process needs to ensure a certain level of quality of the fabricated parts. There are 3 key reasons for the occurrence of irregularities in the final product from composite material:

- machine accuracy,
- the geometry of the object where the laying is performed and
- process parameters.

Thus, this paper focuses on the positioning defects and bonding defects (second reasons). The rest of this paper is organized as follows. In Section B are described the positioning and bonding defects during the LAFP process, mainly gaps and overlaps. Section C focuses on the modeling method of void defects for the thermoplastic composites made by the LAFP process from gap/overlap or process parameters.

A. Machine accuracy –

Tool possiton - how precisely the roller of LAFP/LATL head follows the laying and orientation path; deviation from the predicted orientation of the head can cause separaton of the material from the background where the laying is performed (the robot accuracy). Each from them directly affects the quality of the final products. This section is not the subject of study in this paper.

B. The geometry of the object where the laying is performed

The most common irregularities (possible defects) that occur in the process of laying during LAFP process are shown in Table I

Gap between courses is inadmissible magnitude of the distance between two adjacent courses. Gap between tows is inadmissible magnitude of the distance between two adjacent tows. Overlap is a defect in which two adjacent tows overlap. Missing tow is an empty space where in the reference state there should be a tow. Early add / late cut is early applying of tow at the beggining of a course or delayed cutting of a tow at the end of a course. Late add / early cut is late applying of tow at the beggining of a course or early cutting of a tow at the end of a course.

TABLE I. DEFECTS DURING LAFP PROCESS

Lay-up uniformity features	***Placement features***	***Topical features***
Gaps	Start and end placement position	Splices
Overlaps	Ply edge angularity Ply orientation	Wrinkles, twists, folds
Missing tows	Curvature of the center line of a tow	Bridging, crowning
	Splitting of a tow	Foreign Object Detection (FOD)

Splitting of a tow is a defect that occurs when a tow is ripped and it is laid up with a width smaller than the reference width. In figures 1-5 shows some of the possible errors of the laid tapes, of the possible errors of start and end placement position and possible defects during LAFP process

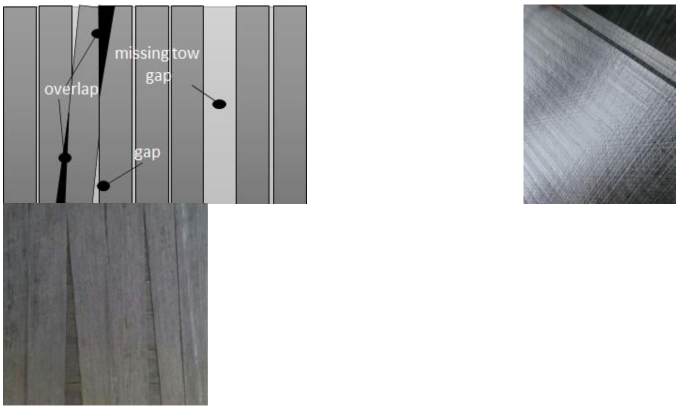
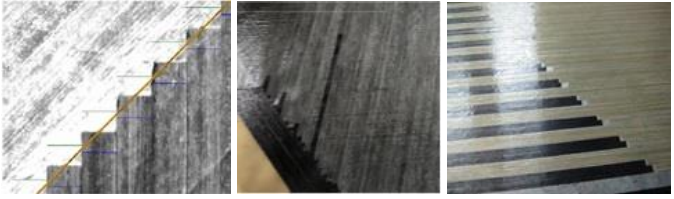


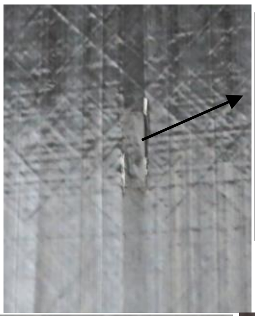
Fig. 1. Laminate missing tow / gaps and overlaps



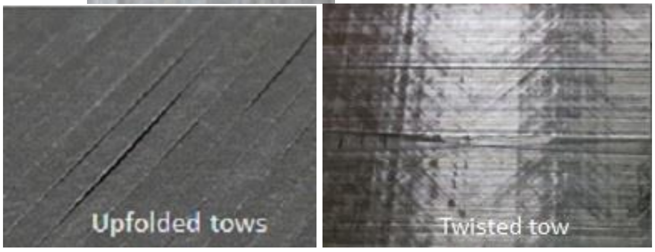
a) Boundary and ply tolerance, late add of a tow

b)Splitting of a tow

Fig. 2. Possible errors of start and end placement position



Splice - a defect that occurs when two tows are joined together, and the sticker is laid up on the composite part



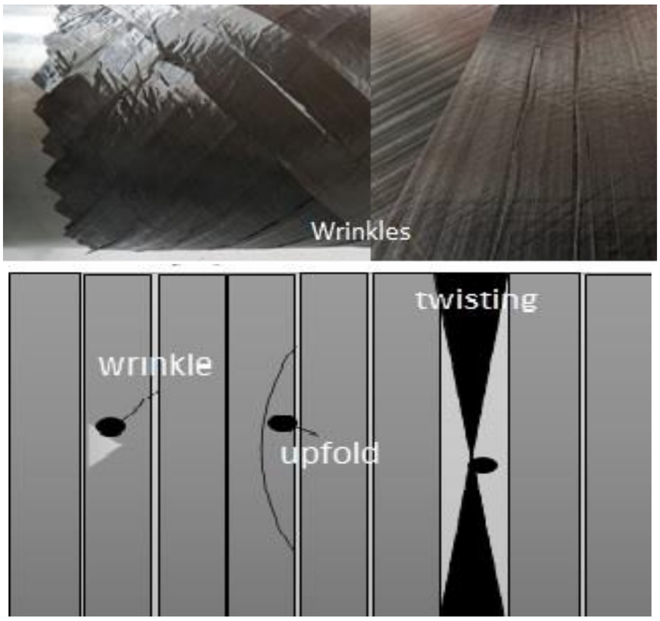


Fig. 3. Wrinkle, twist, fold - a defect indicating different forms of deformations of a tow

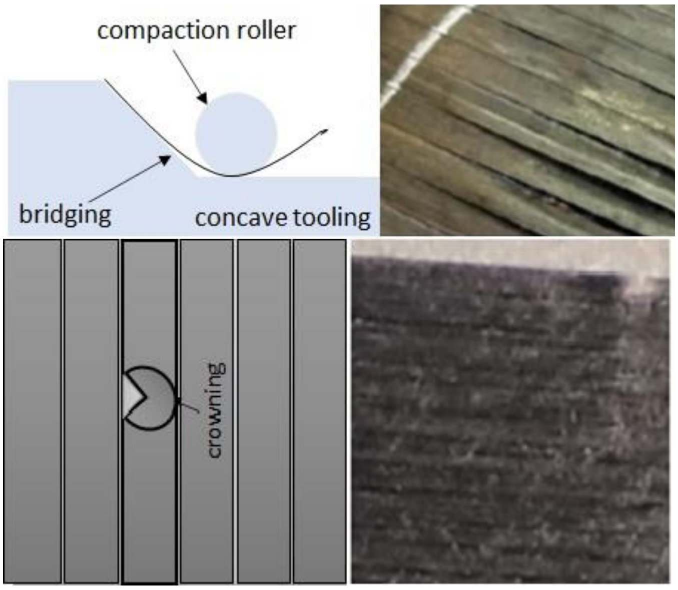


Fig. 4. Bridging and crowning - defects that occur as a lack of contact between the tow and the surface.

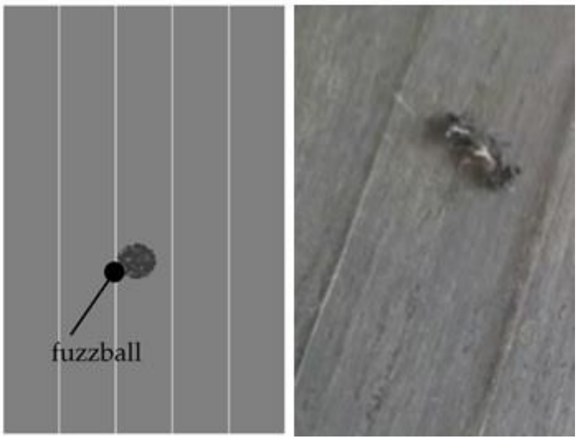


Fig. 5. Fuzzballs - a tangle of fibers dropping on the laid-up part, which accumulate on some parts of the machine during AFP as a result of abrasion of fiber material.

C. *Process parameters*

The mechanical performance of the final parts depends on many factors. Final product from LAFP should be void-free and well consolidated for reliable use in structure. Thermal degradation induced during processing should be minimal in order material to retain its properties. Its crystallinity should be within the recommended range for the material to attain the optimal properties.

Experimental studies were performed with constants process parameters – laser temperature, temperature of tool, compaction force, the angles of laying, the angles of laser beam, dimension of compaction roller, mechanisms for cutting tapes and layup speed. In this paper the impact of the technological parameters of the final product, is not studied. The technological parameters for experiments are taken from trial tests and the experience with LAFP technology.

III. EXPERIMENTAL INVESTIGITION

A. *Materials and equipement*

This study investigated the thermoplastic prepregs: UD pre-preg material Suprem™ T with Carbon-fibre (AS4 carbon fibre) and matrix PEEK (Vitrex 150 PEEK) supplied by Suprem (Switzerland). Specimens were manufacture with thickness 0.14 mm of TPC prepreg.

The laminates were obtained by using a laser-assisted fiber placement head (LAFP), produced by Mikrosam, RN Macedonia. Head is attached to a robot arm (Kuka), as it is shown in Fig. 1. The tape head consists of: (1) a consolidation roller (outer diameter of 60 mm); (2) a tape feed, guidance, tensioning, and cutting system for UD tape; (3) an optic lens connected via a fibre-optic cable to a remotely-located 3 kW diode-laser heat source; and a temperature sensor (pyrometer). On the way to the consolidation roller, the tape is heated up to polymer melt temperature using a laser. The tape is then placed on the tool and consolidated with a temperature-controlled roller (about 19^0C).

Fig. 6. In situ consolidation with LAFP head (Mikrosam D.O.O.).

As a mandrel for the ring specimens a specific cylindrical mandrel was used. The diameter of the mandrel is 400mm, and the length is 500mm.

B. Mechanical analysis

Short beam strength tests were performed for inter-laminar bond strength characterization. In this study, the ASTM D2344 standard was followed.

Samples were prepared using flats from the center where the process had reached steady state. The samples were cut carefully using precision diamond saw. The finished dimensions of the samples were within the tight tolerances of size according standard ASTM D2344. SBS tests were performed with an Universal testing machine. Load was applied with a rate of 1 mm/min. UTM and sample with used test fixture are given in figure 7.

Fig. 7. UTM (universal test machine) and ILSS test (samples No.1 mounted on two supports)

Interlaminar shear strength τ_M, expressed in megapascals was calculated as per the standard (Eq.1)

$\tau_M = 0.75 (F_M / (b \text{ x } h))$…………….(1)

Where F_M is the maximum force observed during the test in newtons, b and h are the measured specimen width and thickness in millimetres respectively.

C. Optical microscope

The void content of composite product is very important parametar that characterizes the quality of the produced composite part. The samples was extracted from each rings. Ten images capture and analysis were performed and they were evaluated for the void content for each of the laminates (rings) manufactured by LAFP process. Seperation of the fibres, resin and voids were performed on selected regions using image analysis software Image J (NIH).

D. DSC

A commonly used method for measuring crystallinity in polymeric materials called Differential Scanning Calorimeter (DSC) is used in this study to validate model predictions with experimental results.

The degree of crystallinity of CF/PEEK laminates was measured by a differential scanning calorimetry (DSC) technique according to ISO 11357-3 [37]. DSC tests were conducted by means of calibrated DSC Instrument equipment from METTLER TOLEDO. The weights of samples extracted from each laminate were in the range of 7–15 mg. Dynamic tests were performed with a heating rate of 10 °C/min from room temperature up to 400 °C. A cooling rate of 10 °C/min was then performed. For the calculation of the degree of crystallinity Xc, the expression (2) was used:

$$X_c = \frac{|\Delta H_m| - |\Delta H_c|}{\Delta H_f\,(1 - w_f)}\ x100\%;\ \left(1 - w_f\right) = w_m \quad (2)$$

where ΔH_m is the enthalpy of fusion at melting point, ΔH_c is the enthalpy of cold crystallization, which is observed in some cases, H_f is the enthalpy of the completely crystalline polymer (130 J/g for PEEK). W_f refers to weight fraction of carbon fibre within the laminate. At least four samples were tested from each laminate(ring), and the averaged data was considered to represent the final degree of crystallinity Xc of each laminate (ring).

IV. RESULTS AND DISSCUSION

A. Manufacture of ring specimens

In these trials was utilized conformable silicone consolidation roller with outer of diameter 60 mm. Consolidation load was applied via pneumatic cylinder, adjusted to provide a 600 N load.

The surface temperature of the tape and substrate in this study were measured for all trials with a thermal camera. Initial experiments were carried out to understand the relationship between process parameters and the quality of the ring obtained in order to optimize the process. Three ring samples were manufactured with different design shown in Figure 8. The process settings are presented in Table II.

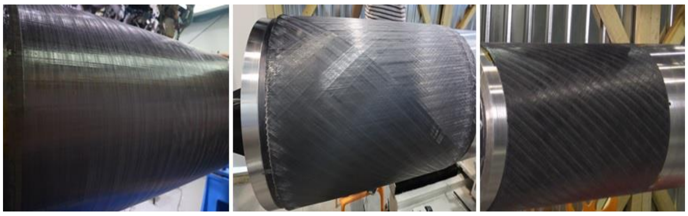


Fig 8. The samples with different design (Ring 1, Ring 2 and Ring 3)

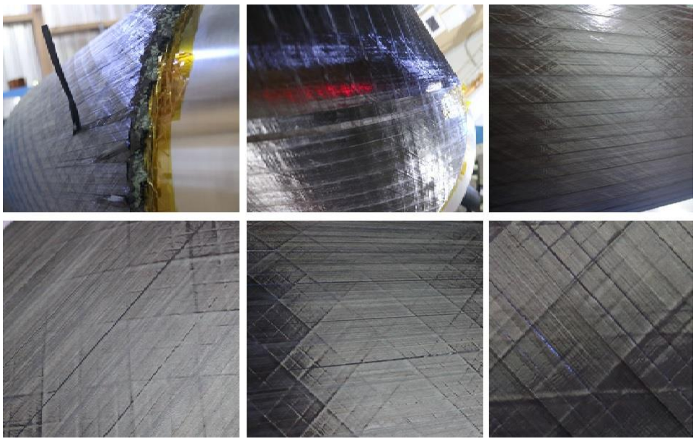


Fig 9. The positioning defects during the LAFP process

TABLE II. PARAMETERS DURING LAFP PROCESS

Constants parameters		*Variables process parameters*	
Lay-up speed	7 m/min	Programmed gap	1.4mm for angles ±30/±45/0°
Laser temperature	430°C		1.6mm for angles ±90°
Compaction force	600N	The design of the specimens	Ring 1 (0/90˚)n
Lead angle	10°		Ring 2 (0/±30˚)
Total angle	17°		Ring 3 (0/±45˚)n

Constants parameters		*Variables process parameters*	
Lay-up speed	7 m/min	Programmed gap	1.4mm for angles ±30/±45/0°
Laser temperature	430°C		1.6mm for angles ±90°
Compaction force	600N		Ring 1 (0/90˚)n
Temperature mandrel	22 °C (RT)		

B. ILSS

Figure 10 shows a typical force-time diagram at ambient temperature for samples No3(1-5). ILSS of composite rings were determined for five specimens for each ring according to equation (1). The average values for each experiment are shown in Table III.

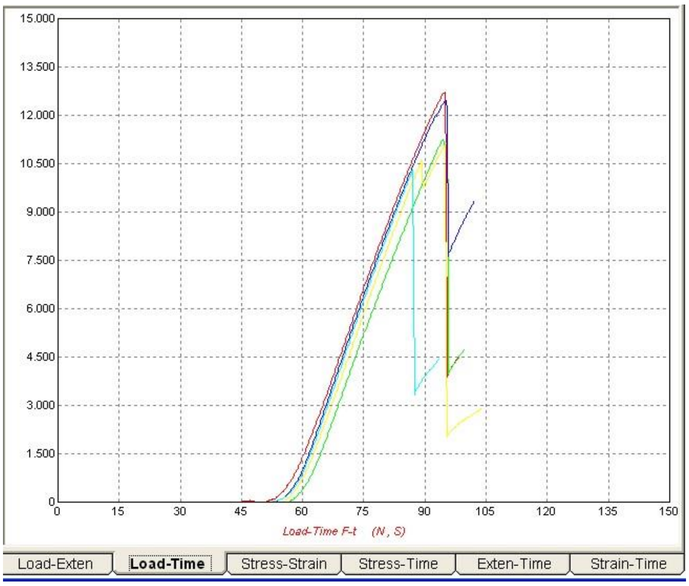


Fig. 10. Force-time diagram of No.3 sample for LAFP (with 5 repeated)

TABLE III. THE RESULTS FOR ILSS TESTS SHEAR STRENGTH FOR EACH RING

sample	***ILSS***	***sample***	***ILSS***	***sample***	***ILSS***
Ring1-1	34.2	Ring2-1	33.1	Ring3-1	53.1
Ring1-2	35.3	Ring2-2	39.9	Ring3-2	46.9
Ring1-3	31.7	Ring2-3	42.4	Ring3-3	51.9
Ring1-4	33.1	Ring2-4	26.3	Ring3-4	46.2
Ring1-5	33.2	Ring2-5	42.3	Ring3-5	42.9
Average	33.5	Average	36.8	Average	48.2

From the results shown in table 3 can be observed that ring specimen No3-1 with ILSS 48.2MPa had the best results. This sample No3 was with 1.4 gap and design (0/±45°) n. In contrary, specimen No1 with gap 1.6mm and angle 90° had shown the worst results, 38% lower value than ILSS from sample No3. The influence of gap/overlap parameters during manufacturing of full section composite parts is reported in [27-30].

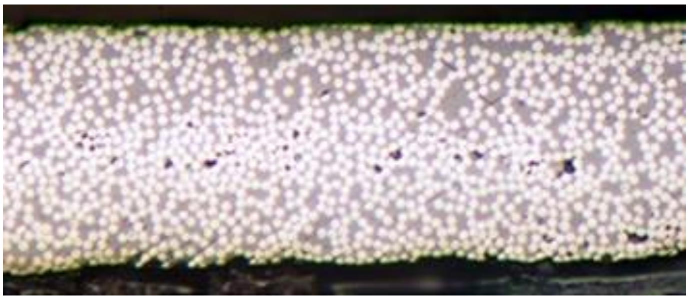
If comparison is made between specimens No2 and No3, it can be seen that design has an influence in mechanical properties ILSS of ring specimens.

Considering the LAFP processing parameters were not optimised in the current study and that the tool temperature was only RT (22 ^{0}C), ILSS can be improved if the mandrel is heated, with ageing or with smaller layup speed in LAFP [27,36]. The results demonstrate that optimisation of mechanical properties using the LAFP process is an complex problem. Processing parameters must be tuned for each material system and each lay-down speed.

Further work will focus on optimising the LATP process.

C. Optical images and calculate porosity

From the results shown by optical microscopy can be observed that ring specimen No3 had the best results and voids <2%.



X200

Fig. 11. Cross-section optical micrographs of lamina UD prepreg Suprem™ T 60% AS4 / PEEK-150 0.14 x 150 (void ~1%)

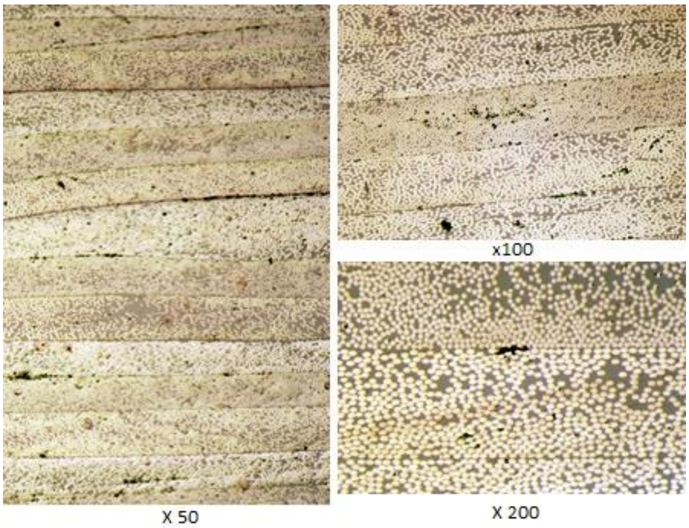


Fig. 12. Cross-section optical micrographs of ring No.3 manufactured in LAFP with in-situ consolidation (voids ~1.6%)

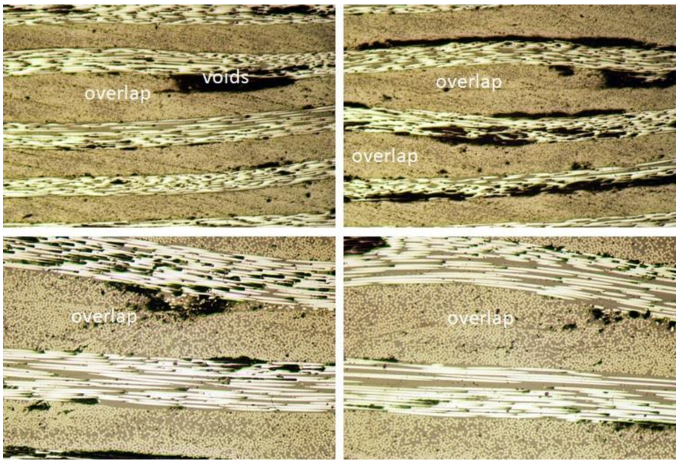


Figure 13. Cross-section optical micrographs of ring No.1 manufactured in LAFP with in-situ consolidation (voids 4%)

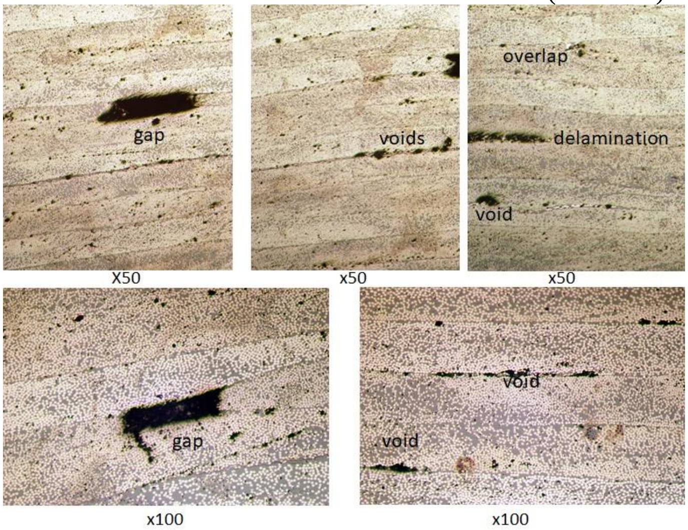


Fig. 14. Cross-section optical micrographs of ring No.1 manufactured in LAFP with in-situ consolidation (voids 4%)

D. Degree of crytalinity DOC (%)

Fig. 15. shows the DSC heating traces of the LAFP Ring 3-1. The laminate LAFP Ring 1 shows a cold crystallization peak at 150-173 °C.

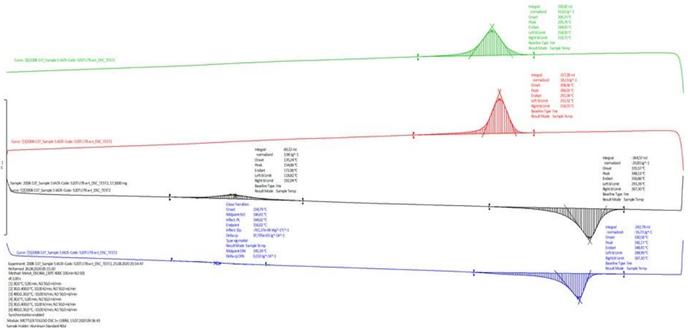


Fig. 15. DSC curves from LAFP Ring 3-1, in two steps

In Table IV are presented values of degree of crystallinity (Xc) calculated from DSC diagrams for all examined specimens: Ring1 (1-4), Ring2 (1-4), and Ring3 (1-4).

TABLE IV. THE RESULTS FOR DOC FOR EACH RING

sample	***Xc (%)***	***sample***	***Xc (%)***	***sample***	***Xc (%)***
Ring1-1	52.47	Ring2-1	37.71	Ring3-1	39.62
Ring1-2	34.32	Ring2-2	30.74	Ring3-2	41.74
Ring1-3	34.92	Ring2-3	34.90	Ring3-3	35.17
Ring1-4	37.44	Ring2-4	37.55	Ring3-4	37.94
Average	39.79	Average	35.23	Average	38.62

A DSC analysis also confirmed that the Ring1, Ring 2 and Ring 3 laminate reached average crystallinity with a value of Xc =35.23-39.79 %. Crystallinity of 35-36% is good enough, but values below this range can cause significant reduction of mechanical properties [10-24].

V CONCLUSION

The experimental procedure described in the present work is suitable to study the influence of the most common irregularities (defects) that occur in the process of laying during LAFP process, on mechanical characteristics of final product.

From conducted mechanical testing can be concluded that the best results in shear strength were obtained with Ring 3. It is assumed that the lower mechanical properties of Ring 1 samples are caused by voids and gaps in the final composite, because process parameters are constants for all investigated samples in this study.

Void contents are within the allowed void tolerance for thermoplastic manufactured with LAFP; however, in further studies targets will be focused to manufacture composite materials with LAFP method with less voids contents and better consolidated laminates.

DOC (Xc) of all rings laminate reached average crystallinity with a value of Xc =35-39% and below these levels mechanical properties would drop off significantly.

Combining different sensors - systems for detection of defect in LAFP process, will become the focus of studying the online detection and controlling defects in the future research.

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