Influence of the Process Parameters on Laser - Assisted Automated Tape Placement Process

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Abstract **Thermoplastic part manufacture by laser-assisted automated tape placement (LATP) process has a high potential for the cost-effective production. Within the frames of this paper it was applied a designing of the industrial LATP process, i.e. planning of the experiments and on the basis of the plan matrix, the specimens were manufactured. Namely, two different thermoplastic prepreg materials were used based on polyphenylene sulfide (PPS) and polyether ether ketone (PEEK) and carbon fibers. The planning of experiments was made separately for processing of these prepreg materials and as the most influenced factors were taken: laser temperature, compact pressure of roller and laser placement angle. For all manufactured specimens the flexural strength was tested and on the basis of the received experimental data it was created the regression equitations which the best describes the processes. This research present and discuss some of laser control system variables and final properties of composite panel specimens.**

Key words: Thermoplastic prepreg, experimental design, automated tape laying, composite plates, flexural strength

I. INTRUDUCTION

The increasing application of thermoplastic carbon composite materials in aerospace and automotive industries results in high requirements to production rate and cost efficiency. Different forms of automated layup processes are used to meet these challenges, utilizing both thermoset and thermoplastic materials. Thermoplastic prepreg deposition by automated fiber placement (AFP) and automated tape placement (ATP) is regarded as the key enabler for the cost-effective production of medium and large parts in today's composite aircrafts [1-4]. Thermoplastic composites are finding new applications in different industrial area thanks to their advantages related to environmental compatibility and processability. The tape placement process is one of the few techniques that have the potential to process thermoplastic composites in large industrial application. The traditional tape placement process for thermoset composites involves a curing step after the placement operation. However, the thermoplastic tape placement offers the additional advantage of in-situ consolidation. The mechanical performance of the final parts depends on many factors. It should be void-free and well consolidated for reliable use in structure. Thermal degradation of the prepreg 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 [5, 6].

Laser-assisted Automated Tape Placement process (LATP) along with out-of-autoclave technology are important to reducing costs involved in making primary composite laminate structures based on thermoplastic material, ranging from a simple flat part to intricate three-dimensional parts. This combination promises fast, reliable and cost-effective manufacturing. Avoiding the autoclave during the curing process not only reduces the costs but also opens up opportunities for the use of lightweight tooling. However, lack of experience in using the LATP machine with laser and along with out-of-autoclave technology results into laminates susceptible of having voids and resin-rich areas. Those are the major problems for successful implementing of these technologies and many investigations are focused for solving that [7, 8].

During manufacturing process, laminate is subjected to several heating and cooling cycles which will result in residual stresses inside the final laminate. Heat input by means of radiative heating offers advantages for these processes and is well established in different forms. Heating and cooling are affected by many parameters such as layup speed, temperature of laser power, layup sequences, ambient temperature etc. A laser-assisted tape placement system is equipped with sensors to measure the temperature and pressure on the profiles improving the bond interface in the nip point region. The recorded temperature and pressure profiles are fed into a bonding model to predict the resulting strength of manufactured thermoplastic laminate [2-5].

The heat is used in all of these processes for different reasons, e.g. to adhere the material to a tool or melt the thermoplastic prepreg component. Different heating technologies have been investigated, including hot gas, infrared, contact heaters and different lasers [9]. Radiation based heating in the form of laser and infrared lamps offer advantages such as high heat flux, precise control, as well as quick response, and therefore are regarded as the favoured heat source for ATP processes [2, 4, 10-13]. Material properties, such as crystallinity and void content depend essentially on the thermal history of the

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laminate, thus also affecting mechanical properties of the final part [2, 12, 14-18]. Therefore, precise knowledge of temperatures is of high interest. Thermal modelling and analysis for radiative heat sources have been thoroughly investigated for specific applications [19- 21].

Automated tape placement of thermoplastic prepreg requires heat input to melt the thermoplastic polymer and weld it to the underlying layer [9, 12, 15]. In order to achieve this, both incoming material and substrate have to be heated [16, 17]. By compressing the material with a compaction roller in-situ consolidation becomes possible, making an autoclave cycle obsolete [5, 7, 9, 11]. Schledjewski [15] assessed different heat sources, including lasers, hot gas, infrared and contact, under different criteria like maximum available power, handling complexity and material degradation, finding that modern diode lasers are the best suited heat source in all important criteria for thermoplastic prepreg layup and the sole drawback being the lack of know-how about them.

The heat output of laser makes them the preferred choice when utilizing polymers that require high processing temperatures like polyether ether ketone (PEEK) (>380 °C) or polyphenyle sulfide (PPS) (343 °C) [7, 11, 14, 21]. Today's laser sources are considered efficient and provide higher heat flux and better process control [21 - 25].

The automated layup is usually performed by a layup head, consisting of material guiding, a compaction unit and a heating system. The layup head is mounted to either a gantry or a robotic arm, providing the movement relative to a tool [2]. Figure 1 demonstrates the general set-up in automated layup with a radiative heat source.

There are a number of parameters that affect the quality of final TPC in AFP process, which influence the thermoplastic composites mechanical properties [3-6]. Welding of semi crystal thermoplastic UD tapes with LATP (laser-assisted tape-placed) process is analyzed in many literatures as well. These studies have led researchers to attempt to measure the temperature distribution near the weld process zone [3-18]. The thermal history of the composite material during processing by LATP is of great benefit to understanding bond quality and the properties that control e.g., crystallinity, void content.

In this study, some variables will be considered. Flexural strength tests were used to determine the bonding strength of tape with laser. This research will present and discuss some of laser control system variables and final properties of flat panel specimens, manufactured with conventional LATP process.
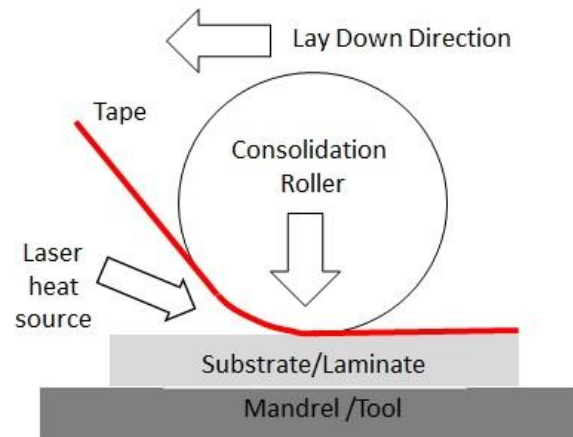

Figure 1. Schematic representation of automatic tape laying process

II.   EKSPERIMENT

In this study for the production of the thermoplastic composite panels, two types of thermoplastic unidirectional prepreg materials (UD1 and UD2) were used. UD1 and UD2 prepreg materials are based on carbon fibres (AS4 carbon fibres) and thermoplastic matrices polyphenylene sulfide - PPS (Ticona 0214 PPS) and poly eter eter ketone PEEK (Vitrex 150 PEEK) respectively for UD1 and UD2 and both supplied by Suprem, Switzerland.

Composite panel specimens with different technological parameters were produced with help of laser-assisted automated tape placement head (LATP), manufactured by Mikrosam, Macedonia. Head is attached to a robot arm, as it is shown in Fig. 2. The tape head consists of: a consolidation roller (outer diameter of 90 mm); a tape feed, guidance, tensioning, and cutting system for UD prepreg tape, an optic lens connected via a fibre-optic cable to a remotely-located 3 kW diodelaser heat source and a temperature sensor (pyrometer).

Figure 2. Automatic laser - assisted of UD1 and UD2 tape laying with machine manufactured by Mikrosam AD

A tape placement process involves pulling of the thermoplastic prepreg tape from a spool through the feed and guide assembly. On the way to the consolidation roller, the tape is heated on temperature (based of the type of polymer) using a laser. The tape is then placed on the tool and consolidated with a roller. During the tape laying, several factors were observed (layup speed, tape temperature, laser temperature, tape tension, the type of laser optics, cooling of mandrels, the cooling of the roller, compact pressure of roller etc.) so that the thickness of ~1,5 mm in the composite plates was attained (8 layers prepreg). The preparation of the

composite/laminate panel was conducted in accordance with the 2^3 full factorial experimental design (FFED) by using of three parameters and two levels of variation. In the FFED, the laser temperature was taken to be the first factor, the second factor was - compact pressure of roller, and the third factor – laser placement angle.

The experimental design was made on the LATP processes for obtaining of laminate panels from UD1 and UD2 thermoplastic prepreg materials and the samples designation are LATP-UD1 for laminate based on UD1 and LATP-UD2 based on UD2. The determination of the factor levels and coding of the variables is conducted in accordance with Table I respectively for the type of materials. Namely, for the first factor (sample LATP-UD1) the low and high levels are set at 360 °C and 380 °C, respectively, for the second factor – at 270 N and 370 N, respectively, and for the third factor – at 22° and 25°. Each factor has two factor levels, a low one and a high one. The low one has the value of (-1), the high one has a value of (+1). There are two factor levels with p = 2 and eight combinations (N= 8, Table II):

$$N = p^k = 2^3 = 8 \qquad (1)$$

where: N = combinations; k = number of factors; p = number of factor levels.

In accordance with the FFED procedure all possible combinations of the variables were tested (8 trials, Table I).

TABLE I.   CODING CONVENTION OF VARIABLES FOR ALL SAMPLES

Sample designation LATP-UD1			
Code	Laser temperature, °C X_1	Laser angle, ° X_2	Compact pressure, N X_3
Zero level, $x_i = 0$	370	23,5	320
Interval of variation	10	1,5	50
High level, $x_i = +1$	380	25	370
Lower level, $x_i = -1$	360	22	270
Sample designation LATP-UD2			
Zero level, $x_i = 0$	450	23,5	457,5
Interval of variation	30	1,5	72,5
High level, $x_i = +1$	480	25	530
Lower level, $x_i = -1$	420	22	385

The FFED allows making mathematical modeling of the investigated process in the vicinity of a chosen experimental point within the study domain [1]. In order to include the whole study domain, we have chosen the central points (zero level, $x_i = 0$) of both ranges to be experimental points. For the samples LATP-UD1 for the laser temperature we have chosen the experimental point to be 370 °C, for the compact pressure – 320 N and for the laser angle – 23,5 ° (which corresponds to previously defined levels). Also, we have chosen the central points for the samples LATP-UD2 (Table I). For the statistical analysis five tests of each combination were realized so the number of replications is five. With that assumption, we have taken the first order linear model with

interactions to predict the response function i.e. the flexural strength of the laminate specimens within the stated study domain.

TABLE II.   FACTORIAL DESIGN 2^3

N	Experimental matrix							
	X_0	X_1	X_2	X_3	$X_1 X_2$	$X_1 X_3$	$X_2 X_3$	$X_1 X_2 X_3$
1	+1	+1	+1	+1	+1	+1	+1	+1
2	+1	-1	+1	+1	-1	-1	+1	-1
3	+1	+1	-1	+1	-1	+1	-1	-1
4	+1	-1	-1	+1	+1	-1	-1	+1
5	+1	+1	+1	-1	+1	-1	-1	-1
6	+1	-1	+1	-1	-1	+1	-1	+1
7	+1	+1	-1	-1	-1	-1	+1	+1
8	+1	-1	-1	-1	+1	+1	+1	-1

An investigation of the effect of technological parameters on mechanical properties of laminate panels was performed. The flexural testing was performed according to ASTM D790, using test rupture (Figure 3). Based on the three-point bending test (3pbt), prepared specimens were elongated till rupture with help of test fixture and the flexural strength is calculated respectively, according to ASTM D 790 standard. The three-point bending tests were performed at room temperature using universal testing machine with max load of 50 kN and loading speed of 5 mm/min. Width and thickness of each specimen was measured with micrometer (with reading to at least 0,0254mm).

TABLE III.   CONDITIONS OF THE EXPERIMENT

N	Factors				
	X_1 (°C)		X_2 (°)	X_3 (N)	
	LATP-UD1	LATP-UD2	LATP-UD1 LATP-UD2	LATP-UD1	LATP-UD2
1	380	480	25	380	530
2	360	420	25	380	530
3	380	480	22	380	530
4	360	420	22	380	530
5	380	480	25	270	385
6	360	420	25	270	385
7	380	480	22	270	385
8	360	420	22	270	385

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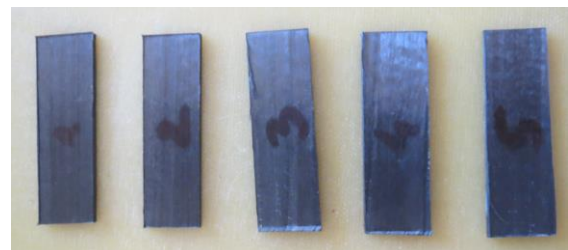**ISSN: 2278-0181**
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Figure 3. Prepared samples and testing of one sample

III. RESULTS AND DISSCUSION

A. Manufacture of LATP UD1 specimens

The test results with five replications of each combination are presented in Table IV.

The statistical parameters: $\bar{y}$- the arithmetic means of the results and S_j^2- the variance of the results were calculated at first. By implementing the 2^3 factorial experimental design we found out that the response function in coded variables, Y, is:

$Y=936,8+31,7X_1-1,47 X_2+42,56X_3+3,31X_{12}+13,09 X_{23}-0,571X_{123}$ (2)

In the experimental design the terms X_1X_2, X_1X_3, X_2X_3 and $X_1X_2X_3$ are the interaction between the factors which might also have the influence on the response, in our case flexural strength (*Y* value). According to table IV, minimal calculated value of parameter's final coefficients for LATP-UD1 is 30,67. So, response function with 5% mistake are represented with equation 3.

TABLE IV.   RESULTS OF THE EXPERIMENTS

N	y_{i1}	y_{i2}	y_{i3}	y_{i4}	y_{i5}	$\bar{y}$	S_j^2
1	975,8	980,4	1028,9	1120,	1079	1036,8	3916,1
2	1026,4	955,6	932,8	862,8	931,1	941,7	13795,7
3	1010,3	1062,2	927,1	987,8	1070,1	1011,5	13709,2
4	837,2	963,4	1014,3	882,9	903,2	927,4	14355,6
5	869,12	815,2	931,2	977,4	926,6	903,9	3934,5
6	783,9	919,4	885,7	913,1	792,4	858,9	17352,1
7	847,68	858,8	919,3	991,1	992,34	921,8	19254,8
8	922,3	901,2	840,9	943,8	853,5	892,4	7773,3
$\sum_{N=1}^{8} S_j^2$							78390,1
$\dfrac{\sum_{N=1}^{8} S_j^2}{8}$							9798,77

N	y_{i1}	y_{i2}	y_{i3}	y_{i4}	y_{i5}	$\bar{y}$	S_j^2
1	975,8	980,4	1028,9	1120,	1079	1036,8	3916,1
S_{bi}^2							244,969
Δbi							30,67

By analyzing the regression equation, it should be noted that the main positive contribution to the *y* is given by the compact pressure of roller and the laser temperature.

The influence of the laser angle affects insignificantly on the flexural strength. The interaction of the two factors, has a smaller effect on the flexural strength than the influence of the factors separately. The interaction of the three factors, with the coefficient of – 0,57 also has a negligible negative effect on the flexural strength. So, they can be omitted in the regression equation:

$Y=936,8+31,7X_1+42,56X_3$ (3)

The test which compares the formula, and the results of the experiments were made by using the Fisher's criteria (Table V). The values for y_p are calculated by using formula 3. If the variability of the model is smaller than the experimental standard deviation, then the model can be accepted and further used (Formulas 4 - 6).

TABLE V.   CALCULATION OF THE DIFFERENCES BETWEEN CALCULATED AND EXPERIMENTAL VALUES

N	$\bar{y}$	y_p	$(\bar{y} - y_p)$	$(\bar{y} - y_p)^2$
1	1036,81	1011,06	25,747	662,8911372
2	941,73	947,66	-5,92913	35,15455756
3	1011,50	1011,06	0,437296	0,191227962
4	927,41	947,66	-20,2548	410,25857
5	903,88	925,95	-22,065	486,8658601
6	858,90	862,55	-3,64488	13,28512606
7	921,83	925,95	-4,11893	16,96559666
8	892,37	862,55	29,82885	889,760008
$\sum_{j=1}^{N}(\bar{y} - y_p)^2 =$				2515,37208

$$F_p \le F_t$$
(4)

$$F_p = \frac{S_{ad}^2}{S_j^2}$$
(5)

$$S_{ad}^2 = \frac{\sum_{j=1}^{N}(\bar{y}_j - y_j)^2}{N-k}$$ N -k = 8-3=5   (6)

Based on the calculation of the differences between calculated and experimental values it was found that $F_p=-0,2567$. The tabular value for Fisher's criteria for P = 0,95; f = (n-1) = 5 – 1 = 4 and N = 8 x (5-1) = 32 is 2,69 and that means that the model is adequate. Because of the fact that the variability of the model is smaller than the experimental standard deviation the model can be accepted and further be used.

Figures 4 shows a typical force - time diagram at ambient temperature for samples (series 1 and series 6) with the highest and lowest values for the flexural strength.

The load-time curves of the specimens series 1 (five replications) are similar and the laminated samples have a linear behaviour up to cracking of the some layers of samples. The curves have an appearance which is like zigzag at the higher values of the force which corresponds to the cracking of the fiber layers. In the case of the specimens series 6 there is a linear behaviour up to cracking of some layers of fibers but the samples are still not destroyed. With continuing of the force, the curves continue to have a view which is like linear up to cracking of the samples. The test results indicated an effect of compact pressure of roller and laser temperature on mechanical properties of composite specimens. Namely, the bigger compact pressure of roller and higher laser temperature led to a higher flexural properties of laminate panels. In a polymer composite, each layer has contribution to the whole strength, and when one of the layers in the structure starts to fail, it cracks the matrix around and there appears an increase in the strain. The strain response of the laminate is restored but the load carrying thickness of the panels is decreased due to the failure of one of the layers. As the wall thickness of the laminate panels is decreased, it cannot carry more load anymore, and fails [26,27].
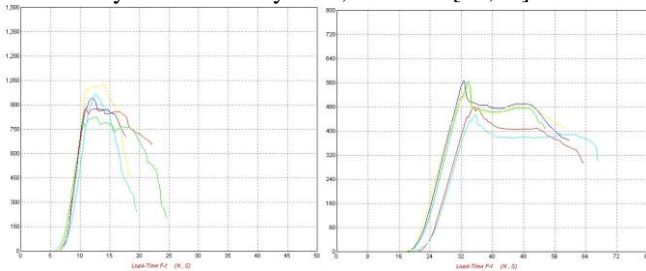

Figure 4. Load -time diagrams for LATP-UD1: series 1 and series 6

B. Manufacture of LATP UD2 specimens

The test results with five replications of each combination are presented in Table VI.

By implementing the 2^3 factorial experimental design we found out that the response function in coded variables, y, is:

$$Y=965,11+68,0X_1-2,28X_2+50,98X_3+25,22X_{12}-19,4X_{13}+43,13+7,92X_{123} \quad (7)$$

According to table VI, minimal calculated value of parameter's final coefficients for LATP-UD2 is 49,20. So, response function with 5 % mistake are represented with equation 5.

TABLE VI.   RESULTS OF THE EXPERIMENTS

N	y_{i1}	y_{i2}	y_{i3}	y_{i4}	y_{i5}	$\bar{y}$	S_j^2
1	1118,7	976,3	1129,9	1184,3	1284,2	1138,7	12522,4
2	990,7	914,2	822,5	1087,4	1061,2	975,2	47264,0
3	954,7	1019,3	1024,5	872,6	1082,3	990,7	25593,4
4	821,7	1087,3	945,4	942,1	1002,4	959,8	37658,5
5	1033,9	954,5	915,5	896,4	1066,9	973,4	5514,9
6	684,0	885,4	708,1	755,4	787,3	764,0	24870,1
7	1159,6	857,5	1034,9	1025,2	1071,1	1029,6	48302,3
8	842,1	1031,6	795,3	837,9	940,2	889,4	36549,9
$\sum_{N=1}^{8} S_j^2$							202197,9
$\dfrac{\sum_{N=1}^{8} S_j^2}{8}$							25274,7
S_{bi}^2							631,869
Δbi							49,2

By analyzing the regression equation, it should be noted that also in the case of samples LATP – UD2 the main positive contribution to the y is given by the laser temperature and the compact pressure of roller. The influence of the laser angle and the interaction of the two and three factors affect insignificantly on the flexural strength and they (factors, X_1, X_1X_3, X_2X_3 and $X_1X_2X_3$) can be omitted in the regression equation:

$$Y=965,11+68,0X_1+50,98X_3 \quad (8)$$

By using the Fisher's criteria, the calculated values by using formula 3 and the results of the experiments (Table VII) were compared. It was found that $F_p=0,1861468$. The tabular value for Fisher's criteria for P = 0,95; f = (n-1) = 5 – 1 = 4 and N = 8 x (5-1) = 32 is 2,69 and that means that the variability of the model is smaller than the experimental standard deviation so, the model can be accepted and further used (Formulas 4 - 6).

TABLE VII.   CALCULATION OF THE DIFFERENCES BETWEEN CALCULATED AND EXPERIMENTAL VALUES

N	$\bar{y}$	y_p	$(\bar{y} - y_p)$	$(\bar{y} - y_p)^2$
1	1138,67	1084,09	54,585	2979,477573
2	975,20	948,09	27,10926	734,911971
3	990,69	1084,09	-93,392	8722,066849
4	959,78	948,09	11,69816	136,8468416
5	973,42	982,13	-8,71007	75,86527534
6	764,03	846,13	-82,1093	6741,933225
7	1029,65	982,13	47,51748	2257,911174
8	889,44	846,13	43,30186	1875,051146

N	$\bar{y}$	y_p	$(\bar{y} - y_p)$	$(\bar{y} - y_p)^2$
1	1138,67	1084,09	54,585	2979,477573
2	975,20	948,09	27,10926	734,911971
$\sum_{j=1}^{N} (\bar{y} - y_p)^2 =$				23524,06405

Figure 5 shows a typical force - time diagram for samples with higher values for the flexural strength (LATP-UD2 series 1) and for samples with lower values for the flexural strength (LATP-UD2 series 6). As it can be seen from the Figure 4, the force - time behaviour of the specimens is similar, namely there is a linear behaviour up to cracking of the first reinforcing layer. The samples series 1 are produced at the high level of the analyzed factors but samples series 6 at the low level of laser temperature and compact pressure of roller and at the high level of laser angle. The test results for LATP-UD2 indicated that the higher laser temperature and bigger compact pressure of roller led to a higher flexural properties of laminate panels. As long as the material is at melt temperature level, the process also facilitates the polymer chain diffusion between the layers to result in good interface section and good mechanical properties. The purpose of the consolidation roller is to compress any of the entrapped air voids by applying sufficient pressure over the melted, low-viscosity tape material. At the same time, the consolidation roller assists in flattening of tape surface irregularities to produce smooth interface contact with the substrate (already placed) layers. An increase in compaction force over the roller could also result in better void compaction and higher flexural strength (or interlaminar strength). Hence, simulations are performed to analyze the extent of improvement. Khan et al. [25] shows the change in the void content for the15-layered laminate laid-up with a force variation from 50 to 5000 N. At low processing velocity, the void deconsolidation phenomena in the heating region prior to the roller demands very high consolidation force and must be supplemented by the sudden roller contact cooling to freeze this state.

As the lay-up at higher velocities with larger power of laser (large temperatures) could increase the production rate, the variation of these two parameters is investigated at other papers [20-25].
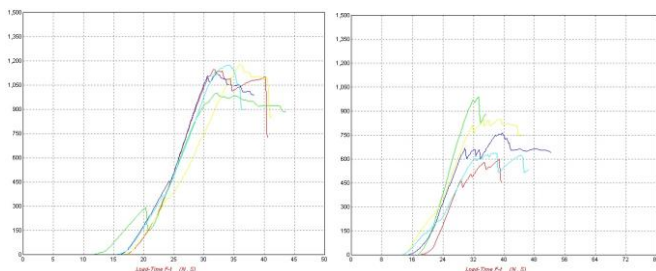

Figure 5. Load -time diagrams for LATP-UD2: series 1 and series 6

V CONCLUSION

The experimental procedure described in the present work is suitable to study the influence of parameters on mechanical characteristics of thermoplastic composites based on PPS and PEEK and carbon fibers produced by LATP process. It can conclude that high quality of laminates made by LATP process depends on the processing parameters fed to the LATP system. Moreover, the compaction force applied during the lay-up process and the laser temperature play a crucial role in achieving of obtaining of defect-free laminates using the thermoplastic (UD1 and UD2) prepreg materials.

Experimental measurements of the flexural strengths of composite flat plates for determined ranges of parameters have been carried out implementing 2^3 full factorial experimental design. Regression equations were established for flexural strengths as a function of the compact pressure of roller, laser temperature and angle of laser. The experimental procedure described in the present work is sufficient to show the influence of the parameters on the flexural properties of thermoplastic composites (LATP-UD1 and LATP-UD2) produced by laser-assisted automated tape laying process. The test results indicated that the change of the compact pressure of roller and laser temperature cause a variation in the final mechanical results, whereas the influence of the other parameter: angle of laser is much lower, and the interaction of the factors has a negligible effect on the response. Very good agreement has been found between experimental and calculated values. It was observed that if the study domain is precisely established (narrow enough), the full factorial experimental design can be employed to give good approximation of the response, i.e. stress of peak values.

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