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Experimental study of steered fibre composite production

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Abstract. The main goal of the study was to design the laminating head for an industrial robot that would be competitive from the aspect of the price and versatility and therefore suitable for the SMEs. A set of experiments were carried out to analyse key parameters during the laminating process of PA12-CF60 material.

Key words: advanced fibre placement technology, automated fibre placement, automated tape laying, fibre reinforced laminates.

1. INTRODUCTION

Because of very good mechanical properties of composite materials (specific strength and stiffness, energy absorption) and their structural capabilities like corrosion resistance, radar transparency, electrical insulation, reduction in tooling and assembly costs, there is a high interest in these materials in different areas such as transportation, construction, aerospace, automobile, and marine industries, and renewable energies [1]. Considering the difficulty of maintaining uniformity and the low strength, high shrinkage, porosity, and voids in the laminates manufactured by hand layup process [2] and the necessity to achieve the high required quality, accuracy, safety, and cost efficiency and at the same time manufacture complex shapes for manufacturing composite parts, there is a need for advanced tooling machines [3].

Today, by applying the Automated Tape Laying (ATL) technology and Automated Fibre Placement (AFP) techniques, it is possible to manufacture different composite parts of mechanical components with high accuracy, flexibility, and minimum waste [4]. The ATL technology is an automated layup process for large-scale manufacturing of composite components by constantly laying the heated composite fibre tape on a mould by a compaction roller according to the predefined orientation [5]. This technology is used to manufacture large composite components with flat and not very complex geometries. Compared with the hand layup technique, the ATL technology enables repeatability in production, higher accuracy in placing the fibres in the desired position, and reduction in waste and costs [6]. The ATL process consists of a cutting system to cut the tape in the desired measure and location, guide rollers to move the tape through the cutting system, a heating system to melt the matrix material and increase the tack level for adhesion, and a compaction roller to press the tape on the mould [7] (Fig. 1).

In general, both thermoplastics and thermosets are used in the ATL process [8]. Before full-scale production, the final product should go through some mechanical tests, such as tack test, tensile test of the seam, porosity test, etc., to check the achieved mechanical properties. Tack is the tendency of the prepreg to adhere to the previous layer or the mould surface, and the test is to

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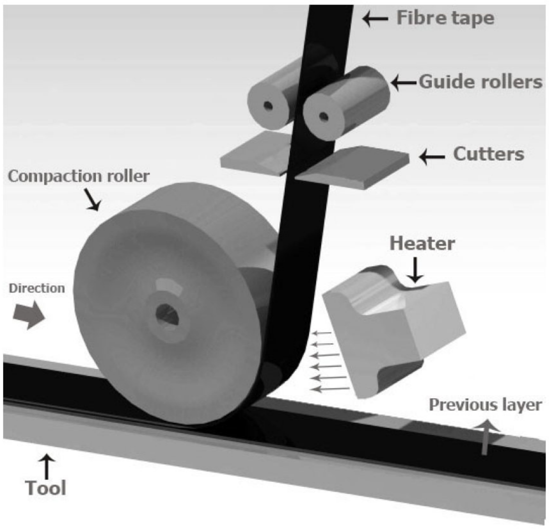

Fig. 1. Scheme of the ATL system.

determine the strength of the adhesion [9]. Depending on the manufacturer, there are different methods for testing the tack level of the layers. The level of tack can be evaluated by the peel-off test but also by a simple tensile test measuring the strength of the seam [10]. Crossley et al. [11] point out the most important factors influencing the tack level characteristics: the temperature, feed rate of the fibre, release agents, and environmental factors, e.g. the moisture. Campbell [12] states that a prepreg containing higher moisture is tackier than the one containing lower moisture. Increasing temperature raises the tack level of the fibres. Thus, the sufficient heating temperature should be achieved before the laying process is started [11].

Grouve et al. [13] used a mandrel peel set-up to test the strength of the laminates manufactured by laser-assisted tape placement. Their work indicates that by increasing temperature and feed rate the bond strength of the laminates increases. Rao et al. [14] employed a floating roller peel test to determine the tack level of the first ply and the mould surface, and found that the temperature has the highest impact on determining the peeling force, while the feeding rate has a low impact.

2. PROCESS PARAMETERS

Based on the literature [15,16], the main operational parameters of the ATL technology considered herein are the following:
- compaction force
- heating temperature
- laminating speed.

Some other important parameters are
- the radius of the roller
- the material and the coating of the roller
- the curvature of the mould, etc.

The following part of this paper concentrates on testing the two main parameters: the laminating speed and the compaction force. A specially designed testing device was used.

3. TESTING

3.1. Test setup

During the experimental study two main operation parameters – compaction force and laminating speed – were investigated on a carbon fibre reinforced polyamide material PA12-CF60 tape with a thickness of 0.1 mm and width of 25.4 mm. The melting point of this material is 180 °C. The tests were carried out as a continuous process and parameters were observed during the laminating. The tape was cut into the correct length and positioned on an aluminium mould while ensuring that the overlay surface area during every test attempt was approximately the same. The test piece can be seen in Fig. 2.

For maintaining the estimated contact area of 645 mm^2 during the rolling process both parts of the tape were fixed to the aluminium mould. The test setup can be seen in Fig. 3. For controlled laminating movements the test device was attached to a CNC milling machine. In order to maintain and vary the necessary compaction force a pneumatic cylinder and a pressure regulator were used. A curved ceramic infrared heater Ceramicx HTE 500 with 500 W output power was used as a heating source. The temperature was observed with an Optris CS LT contactless infrared pyrometer on the contact area during the laminating process. An Arduino based controller was used to control the infrared heater and to get readings from the pyrometer. At first the infrared sensor was meant to be used as a feedback to the Arduino, but it appeared that the heat inertia of the heater was too high to be controlled via a feedback system.

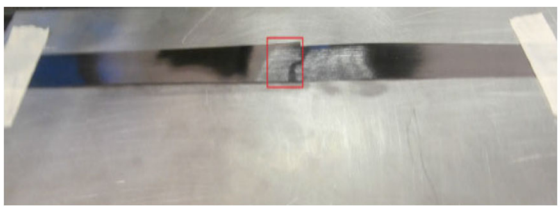

Fig. 2. Test piece. The red rectangle indicates the location of the contact area between two tapes.

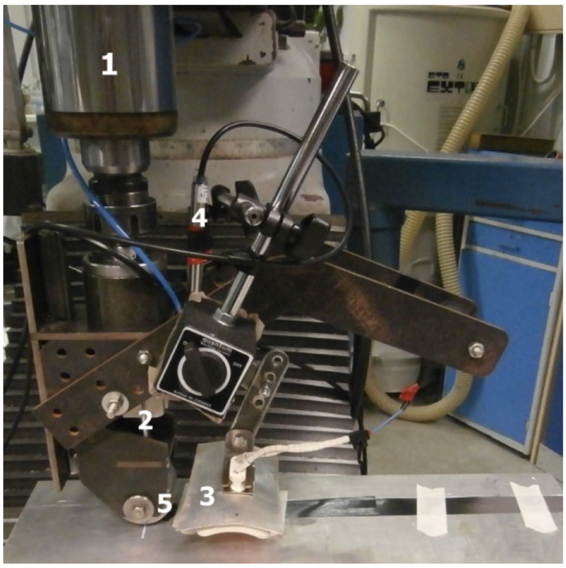

Fig. 3. Test setup. 1 – CNN milling machine, 2 – pneumatic cylinder, 3 – infrared heater, 4 – pyrometer, 5 – consolidation roller.

A consolidation roller made of steel S355JR was used for transmitting the compaction force from the pneumatic cylinder to the contact area between two tapes.

The tests were carried out as follows: (1) Both parts of the tape were fixed to the aluminium plate imitating the mould. (2) The heater was warmed up to a stable temperature. (3) While maintaining a constant laminating speed with a CNC milling machine, the contact area between two tapes was heated with the infrared heater and consolidated with the compaction roller. (4) The consolidated test piece was removed from the aluminium plate. (5) Test pieces were torn apart with the tensile testing machine and investigated from the aspect of adhesion.

3.2. Tests

As our previous studies ([17,18]) showed, the optimal laminating temperature range should be between 200 and 230 °C. Therefore the laminating temperature during the laminating process was kept in that range by adjusting the power of the infrared heater. To simplify testing the range ±15 °C was considered sufficiently precise to carry out the experiment. Therefore the temperature was taken into account as a constant.

To find the correlation between the consolidation force, consolidation speed, and tensile strength of the test piece, the full factorial design of the experiment was performed. To minimize the effect of random factors on the test results, every test set was repeated twice. Since a pneumatic cylinder and a manometer were used for measuring the compaction force, the force was converted from the air pressure. The levels were as follows: (1) 1 bar – 80 N; (2) 4 bar – 322 N; (3) 7 bar – 563 N.

The levels of the laminating speed were as follows: 0.3 m/min, 0.4 m/min, and 0.5 m/min. Test results are presented in Table 1.

The results show that the strongest seam was achieved with 322 N compaction force and 0.4 m/min laminating speed. The tensile force with these parameter values was 6945 N. However, as it can be seen in Table 1, the results are scattered.

The reason of scattered results is probably an insufficient control of the process parameters, but also numerous outside factors, for example improper alignment of the roller and the mould and improper control of the material temperature, may have had an influence on the process. Although the temperature during laminating was constantly monitored with the sensor, it is possible that the sensor did not reach the actual consolidation zone, which may have caused some deviations from the real values. Also, in principle variations in the surface area of the seam and misalignment of the test strips are possible.

A separate issue is using a proper heat source. In the current study an electrical ceramic infrared heat source was used. It is well controllable by means of controlling the power of the element. Also the power of 500 W seems to be enough at low laminating speeds. The disadvantage of that type of heat source is that it is difficult to focus the heat beam and it generates a lot of excessive heat that cannot be used in the process and therefore has a rather adverse influence on the process parameters by heating up the surroundings.

Table 1. Results of the tensile test

Test	Compaction force, N ± 20 N	Laminating speed, m/min	Tensile force, N ± 0.5%
1	80	0.3	2103
2	80	0.3	5730
3	80	0.4	1726
4	80	0.4	737
5	80	0.5	4915
6	80	0.5	2313
7	322	0.3	2848
8	322	0.3	3336
9	322	0.4	6360
10	322	0.4	6945
11	322	0.5	905
12	322	0.5	5333
13	563	0.3	4340
14	563	0.3	4240
15	563	0.4	2712
16	563	0.4	6315
17	563	0.5	1061
18	563	0.5	3352

Based on factors listed above, the next steps that should be taken into consideration in the development of the new laminating head are the following:
(1) The force control/position compensation can be left as it is – it is accurate enough;
(2) The heat sensor has to be positioned so that it would measure the values as close as possible to the consolidation area. It has to be guaranteed that the excessive heat from the heat source does not influence the operation of the sensor;
(3) The key factor in this process – the heating element – must be improved. A fast reacting infrared heater, or even better, a laser beam should be used.

4. CONCLUSION

A laminating head for an industrial robot with a competitive price and versatility has been developed. An experimental study was performed in order to determine the relationships between the main laminating parameters – laminating temperature, consolidation force, and consolidation speed – during the continuous process (in situ laminating). Despite the fact that a proper correlation between the parameters was not found due to the scattering of the results, the results of the experiments show that the values of the parameters used on this specific device are not totally off the scale. The maximum force achieved, 6945 N, which is close to the tensile strength of the tape itself with 7404 N ± 62 N, proves the fact.

It can be concluded that a ceramic infrared heater with high heat inertia does not provide satisfactory temperature control for laminating PA12-CF60 tape at higher speeds that are needed to make the device usable in industry.

5. FUTURE STUDY

The current study is of completely experimental character. However, the theoretical and numerical analysis of the steered composite has been planned. The numerical methods developed by the workgroup for analysis of composite laminates and FGM structures [19,20] are planned to be extended for analysis of steered fibre composites. Also, the results covering optimization algorithms and methods for composite structures [21–23] can be employed for fibre angle determination in designing steered fibre laminates. The experimental and numerical evaluation of the strength and stiffness properties of steered fibre materials and structures are activities that should follow the design and manufacturing process. Here special attention should be paid to robustness of the design and sensitivity analysis.

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Muutuva kiusuunaga komposiitlaminaadi valmistamine

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Käesoleva artikli peamiseks eesmärgiks on lamineerimisseadeldise arendamises astuda samm lähemale tööstusrobotile, mis oleks piisavalt universaalne ja hinna poolest kättesaadav väikestele ning keskmise suurusega komposiitmaterjalidega tegelevatele ettevõtetele. Artiklis kirjeldatud katsete eesmärgiks oli välja selgitada lamineerimisprotsessi peamiste parameetrite vaheline seos materjali PA12-CF60 lamineerimisel.