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Transport and Aerospace Engineering doi: 10.1515/tae-2015-0001
2015 / 2

The Impact of Methods of Forming on the Mechanical Properties of Fiber-reinforced Polymer-matrix Composite Materials

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Abstract **– The aim of this paper was to analyze how different techniques of production of fibrous composite materials affect the quality and strength properties of composite laminates. In this study, we use experimental data concerning a composite fabricated with the by hand lay-up and vacuum bagging method. The composites have a polyester matrix (Firestop 8175-w-1) reinforced with mate-glass fiber fabric [0/90/0/90] E glass fiber, respectively. The process parameters and criteria were determined before the samples were cut, namely the amount and soaking time of the composite with the polymer resin.**

Keywords **– Composite, fibrous composite materials, forming, strength, technology.**

I. Introduction

The specific applications of fiber composite materials (FCM) in various industries (widely used as the primary construction material in the aerospace and automotive industries) pose an important problem: the need to develop the accuracy of the techniques of computational models [1]–[4] and in particular analytical solutions or fatigue strength parameters [5]–[7]. There are many models describing the destruction of polymer composites. In addition to the statistical models and phenomenological defining properties of composite materials, homogenization models are used [8] – model of P. Abolins [9], the Wilczyński-Lewinski model [10], the model by HRT (Hasin, Rose, Tsai [8], [11]) – which allows to obtain the specific properties of the material based on the material characteristics of individual phases and their share volume in the composite.

The description of the mechanical properties of components such as FCM fiber bundle fiber and laminate is a complex process which in most of the proposed models takes into account only the initial stages of structure complexity. At the transition from one structure to another (non-woven fiber bundles, unidirectional composite) in most cases a reduction in the strength of the composite is observed.

The verification calculation does not allow us to conclude that the current models accurately describe all the material constants. Therefore, the only reliable method of obtaining the data is experience. This occurs due to the technological process, uneven location (in the whole volume) of fibers, local discontinuity of fibers, lack of adhesion to the fiber-matrix border as well as imperfections in the dies and form of voids, micro-cracks or slots [12].

II. Materials and Methods

The objects of the study were the following: composite fiber material formed by contact (composite I) and composite material produced by injection of resin (by sucking) into the mold (i.e. Vacuum bagging – composite II) with reinforcement in the form of mate-glass fabric weighing 600 g/m^2 (Fig. 1 [13]).

The four-symmetric composite I and composite II, in addition to strengthening, were exposed to unsaturated polyester resin manufactured by BÜFA company (Firestop @ 8170-W1). The resin is based on DCPD acids (containing ATH and a special supplement locking styrene emission, halogen) which is used to produce laminates with reduced flammability (compliant with EC 95/28) and good mechanical properties (Table I [13]).

Fig. 1. Mate-glass fabric as reinforcement of composite molded contact and vacuum bagging.

The composite of symmetrical [0/90/0/90] structure was produced in the Department of Composites, “BELLA” company. The technological parameters of molded laminates are presented in Table II.

TABLE I

PARAMETERS OF LAMINATE CONTACT MOLDING (MANUAL METHOD) AND VACUUM BAGGING METHOD

Technology	Hardener, %	Time of forming, h	Gelling time, min	Additional treatment
Composite I (Contact moulding)	Butanox M50, 40	24	60 (T = 22–23 °C)	30 °C (16 h)
Composite II (Vacuum bagging)	Butanox M50, 40	24	60 (T = 18–20 °C)	30 °C (16 h)

TABLE II

TECHNICAL SPECIFICATIONS OF FIRESTOP @ 8170-W1 RESIN

Properties	Norm	Value
Density at 20 °C, g/ml	DIN 53 217/2	1.25
Ignition temperature, °C	DIN 53 213	32
Viscosity at 20 °C Brookfield RV/DV-II Spl 4. rpm 20, MPa·s	ISO 2555	800–1400
Monomer content, %		40–42

The materials were formed by the combination of methods, vacuum bagging lamination by hand, whereby the reinforcement was arranged to the pre-prepared form of a flexible bag (Fig. 2) [14], [15]. It was done by means of a brush (and a shaft) soaked in the composite reinforcement layer (as mate-glass fabrics) resin until the desired thickness of the laminate.

The steps and molding time of the polymer matrix composite (ceramic flat size 1000*300 mm) are shown in Table III. However, in the vacuum bagging method (Fig. 2) after locating the strengthening in the form of a handheld saturation mixture of resin and hardener (3), the laminate is covered with a flexible film (2) or rubber bag which is sealed at the edges by pressing (5) into the mold (4) and is connected by a fitting (1) to a vacuum pump. As a result of the negative pressure, the air contained in the molded composite is sucked by the vacuum pump. Thus, the manufactured product is cured at ambient temperature. This method allows to remove bubbles to strengthen and increase the share up to about 55 % [12], [13].

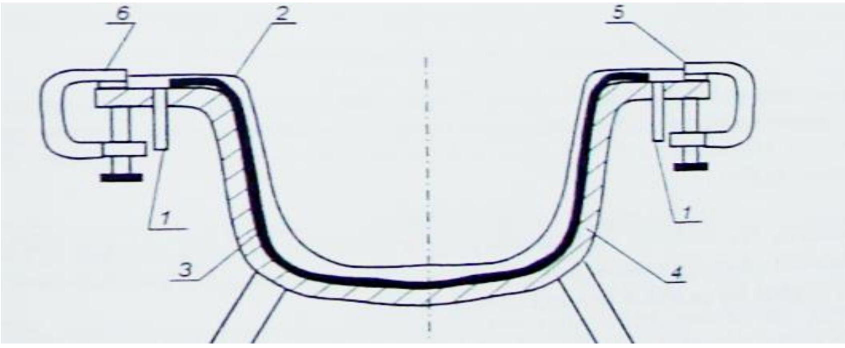

Fig. 2. Diagram of vacuum forming apparatus.
1 – vacuum nozzle, 2 – flexible bag, 3 – reinforcement saturated with a mixture of resin and hardener,
4 – form, 5,6 – terminal.

With the laminate prepared in this way samples were cut according to DIN EN ISO 527 (Fig. 3) at different angles cut further boost (Fig. 1) with a length measuring of 150 mm by milling using CNC support. The following markings samples were subjected to static tensile test:

"POLY1_1(2) –xx" and "POLY2_1(2) –xx",

where "POLY1" and "POLY2" mean composite I and composite II with different cutting angles: 1 – 0°; 2 – 90°, respectively, along with sample number "xx";

The samples were then subjected to a static tensile test (according to ISO 14129:1997) at a stretching speed of 2 mm/min on a universal testing machine Instron8501 in the Laboratory of Material Strength, Center for Laser Technologies of Metals, Kielce University of Technology.

TABLE III

STEPS OF PREPARING FIBER COMPOSITE MATERIAL BY THE CONTACT MOLDING METHOD

No.	Steps of FCM forming (time)
1	Preparation of laminate components (20 min) 
2	Imposition of the distributor on previously prepared in a paste form and polishing after the imposition of the form release agent form of laminate (3 layers: 3 x 20 min) 

3	Preparation and arrangement in the form of dry resin impregnated strengthening (up to 5 min)  
4	Imposition of the remaining layers of fabric (mate-glass fabric: composite I) or (biaxial composite II) – about 25 min 

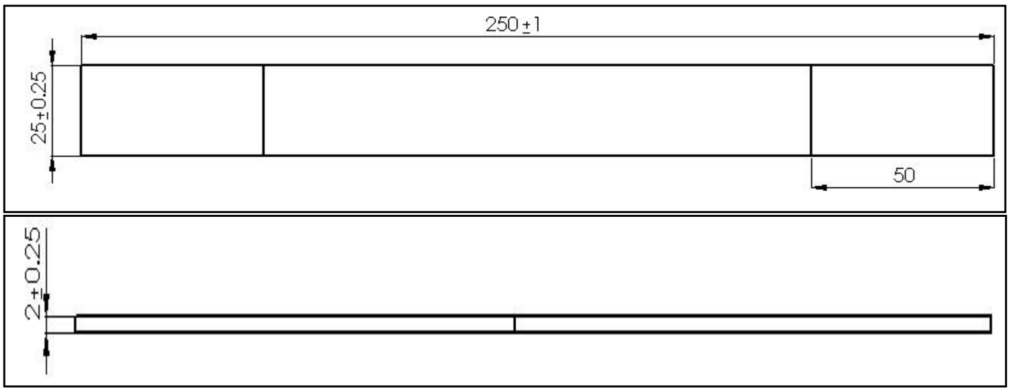

Fig. 3. Geometric dimensions of the samples: POLY1_1(2)-xx and POLY2_1(2)-xx.

The analysis of the structure impact on mechanical processing was carried out using the metallographic methods of quantitative metallography. The resulting samples were cut for metallographic actual cutter's BUEHLER IZOMET LS model by using a composite disc (type 15HC). Mounting and samples by vacuum cold EPO-THIN. After grinding, the sample was polished using the preparations of the company BUEHLER based on polycrystalline diamond abrasives. The quantitative characteristics of the composite structures produced were determined on the basis of a microscope image with a maximum magnification of 500 times.

III. Analysis of Results

The test results obtained from the static tensile test of the FCM prepared by hand lay-up (Table IV) have quite a significant scatter in mechanical properties in comparison with the vacuum bagging method (Table V).

Defects at the production stage deteriorate the properties of the molded laminates (as a result of errors or other technology of secondary operations). Along with the increase in the angle of 0–90° the strength of the composite was enhanced. The highest average strength determined at the level of 144.95 MPa for the 2-way FCM [0/90/0/90] with load acting at an angle of 90° with respect to the strengthening of the molded vacuum bag. It should be noted that the above relationship also relates to the 2-way FCM [0/90/0/90] produced by hand with less σ average of about 15 %.

We observed changes in the volatility of strength laminate molded by the contact method which indicates that this method does not guarantee reproducible results. The above is highlighted with significant volatility changes in strength characteristics as illustrated in graphs σ-ε (Fig. 4).

TABLE IV

SUMMARY OF THE DATA ON SAMPLES LOADED AT AN ANGLE DURING THE USE OF THE HAND LAY-UP METHOD

Sample	σ_0, MPa	Sample	σ_{90}, MPa
POLY1_11	–	POLY1_21	–
POLY1_12	–	POLY1_22	117.60
POLY1_13	127.40	POLY1_23	145.10
POLY1_14	116.00	POLY1_24	130.50
POLY1_15	109.30	POLY1_25	110.12
Average	117.57	Average	125.83
Sample	E_1, MPa	Sample	E_2, MPa
POLY1_11	–	POLY1_21	–
POLY1_12	–	POLY1_22	11.27
POLY1_13	9.49	POLY1_23	11.57
POLY1_14	9.82	POLY1_24	12.08
POLY1_15	9.79	POLY1_25	11.26
Average	9.70	Average	11.55

TABLE V

SUMMARY OF THE DATA ON SAMPLES LOADED AT AN ANGLE DURING THE USE OF THE VACUUM BAGGING METHOD

Sample	σ_0, MPa	Sample	σ_{90}, MPa
POLY1_21	154.60	POLY2_21	135.50
POLY1_22	123.50	POLY2_22	148.32
POLY1_23	–	POLY2_23	148.50
POLY1_24	129.40	POLY2_24	143.20
POLY1_25	117.90	POLY2_25	149.25
Average	131.35	Average	144.95
Sample	E_1, MPa	Sample	E_2, MPa
POLY1_21	12.23	POLY2_21	13.65
POLY1_22	11.20	POLY2_22	13.52
POLY1_23	–	POLY2_23	12.60
POLY1_24	11.80	POLY2_24	15.81
POLY1_25	11.38	POLY2_25	14.96
Average	11.65	Average	14.11

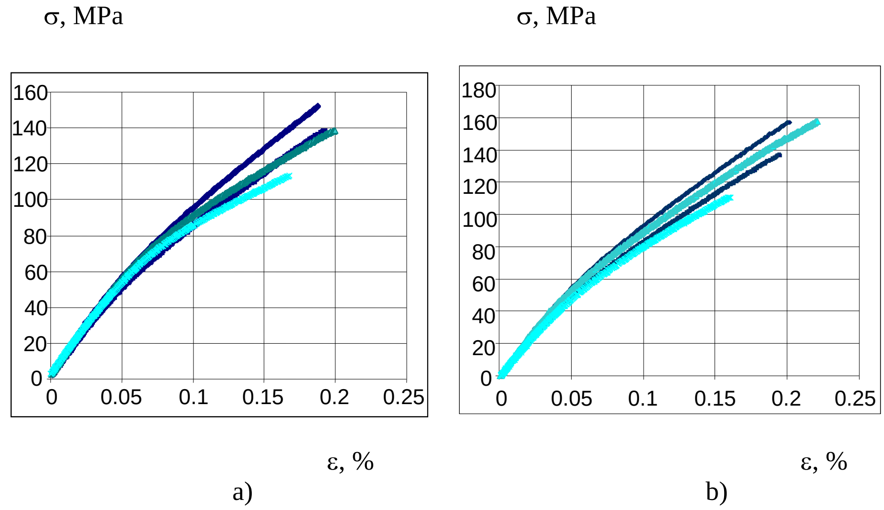

Fig. 4. Spread properties of the FCM samples; the example diagrams of σ-ε laminates made by hand and using the vacuum bagging methods and the direction of the fibers: parallel 0° (a) and perpendicular 90° (b).

The accumulation of defects and damage of the produced structure are shown in Fig. 5. The loss of adhesion on the contact boundary fiber matrix (the so-called debonding) is damage to the microstructure appearing at the earliest stages of the process of polymer composite degradation. At this stage of material destruction, adhesive cracks do not have a large effect on the macroscopic characteristics of the material but usually are the first link in the chain of material destruction. Damage to the boundary layer occurs as a result of exceeding the critical stress – normal stresses to the lateral surface of the fiber and the tangent ones (shear causing the contact zone with the warp fibers). They usually occur on the edges of finished parts, introduced by such operations as cutting (using a mechanical support CNC, abrasive water jet [16]) or as a result of not meeting the cure times and too low portion of resin provided between the layers of the mat. The laminate produced by the vacuum bag (Fig. 3) is more even and 20 % thinner than the laminate formed by the contact method [17].

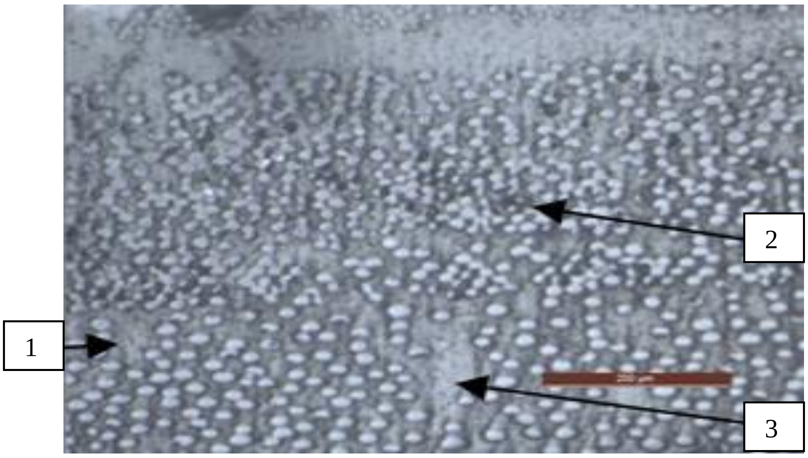

Fig. 5. Microstructure of defects in the form.
1 – microcavities; 2 – microcrack components; 3 – voids in the polyester matrix.

This is due to the technological process, uneven location (in the whole volume) of the fibers, the fibers local discontinuity, lack of adhesion to the fiber-matrix border, as well as imperfections in the matrix in the form of voids, micro-cracks, or fissures.

All faults and phenomena (deriving from the process) worsen the mechanical properties of the material as well as aesthetic value of the product. These phenomena are very sensitive to the quality of FCM structure and imperfections in the molding formed of a material.

VI. Conclusion

The following has been found:

- higher strength (about 15 %) and lower scattering strength of the sample made of composite II (vacuum bagging) than of the one made of composite I (contact) with the polyester matrix;
- the impact of architectural arrangement of layers in the composite polymer matrix (with the increase of the angle from 0–90º increases the strength of the composite, 2-way);
- smoother and 20 % smaller than the thickness of composite II (composite molded and hand lay-up);
- the volatility of changes of strength laminate molded contact (that does not guarantee reproducible results), which is not observed in determining the strength of the samples produced by vacuum bagging;

Experimental verification studies allow concluding that none of the existing models describes all the material constants with reasonable accuracy.

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