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The Influence of Pressure in the Infusion Method Upon Mechanical Properties of Polymer Composites

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ABSTRACT

In the modern aerospace industry, a steady increase in the share of composite materials is recorded every single year. Polymer layer composites seem to be the ones that are used most commonly in aviation. There are multiple methods of producing this type of materials, of which the most commonly used methods are as follows: the infusion method, the negative pressure bag method and the hydraulic press method. The infusion process makes it possible to obtain composites with the best mechanical properties. In the infusion process, the mould is pre-prepared (together with the reinforcement made of the material from which the composite is made, e.g. carbon fibre), which is tightly closed in a negative pressure bag, and the equipment supplying the previously mixed resin with hardener is connected to the injection points. The negative pressure generated by the negative pressure pump in the mould prepared in this way (negative pressure bag) makes the previously prepared resin seep through the reinforcement material. Various negative pressure levels can be used. This work describes the effect of the applied negative pressure level on the obtained mechanical properties of a composite reinforced with carbon fibres. It appears that the best visual properties of the composite material are obtained with the use of indirect (optimal) negative pressure but the best strength properties with the use of maximal negative pressure.

Keywords: sandwich composites, composite manufacturing processes, infusion method.

INTRODUCTION

The use of modern materials, including composites, continues to steadily increase in today's aerospace industry [17]. The choice of composite materials is affected by their unique properties [3, 5]. The most commonly used type of these materials is sandwich composites [2, 8]. There are a number of methods for producing them: the hydraulic press method, the negative pressure bag method and the infusion method [1]. The infusion technology is based on the use of negative pressure, which both induces the process of spreading the liquid matrix inside the laminate and ensures adequate pressure during composite manufacture [16]. This technology is currently one of the most advanced and widely used methods for composite manufacturing [13]. Often this method competes with and sometimes replaces autoclave-based composite manufacturing processes due to a significantly lower cost of producing composite materials. The infusion process finds an increasing use in modern industry due to its ability to distribute the resin evenly without any excess, the repeatability of the characteristics of the manufactured materials and the 'cleanliness' of the process.

Negative pressure-based composite technology provides a number of benefits, including automation and acceleration of the infusion of multiple layers of reinforcement. Infusion makes it possible to avoid contact with the liquid matrix ('cleanliness of the manufacturing process'), which is extremely important in the case of, for example, polyester resin, and in producing not only simple but also complex shapes of composite items. The advantage of infusion technology is that it can produce a laminate with a very high percentage of fibre content (up to 70% fibre by weight), thus creating a very strong and rigid structure with low weight. Infusion is also a very efficient manufacturing process for complex laminates with multiple layers of fibres and core materials.

The infusion process begins by placing dry sheets in the mould. Once the mould is sealed with a negative pressure bag (often by taping the edges with butyl tape), a tightly sealed system is achieved. In order to prevent the finished laminate from sticking to the surface of the mould, a release agent (e.g. in the form of wax) should be applied to the mould before layering the material. In order to ensure an undisturbed flow of resin with the hardener and to avoid the presence of air bubbles in the finished laminate, the mould surface should be provided with as little roughness as possible, which is achieved by polishing its surface. Once the dry sheets of reinforcing fabric, delamination fabric and mesh sheet, which accelerates the flow of resin and distributes it evenly inside the reinforcing fabrics, have been laid, the auxiliary elements (valves, tubes) are laid. Along the layers of fabric (sheets), spiral tubes are placed on both sides to correctly feed the resin and maintain negative pressure in all areas of the mould (the number of these elements depends on the complexity of the surface of the laminate to be produced). The resin distribution system inside the laminate should be designed to prevent voids (i.e. areas where the resin and hardener have not reached) from being closed by the flowing matrix. Once the negative pressure bag is sealed, its tightness is checked. If there are no leaks, the resin feed valve is activated and the resin begins to seep spontaneously through the pre-laid layers of material as a result of the negative pressure. The negative pressure allows the resin to flow and distribute evenly through individual layers. When all layers are fully saturated, the valves are closed and the laminates are cured at room temperature for a period of time based on the characteristics of the used resin/hardener mixture.

Once the composite has been cross-linked, the negative pressure bag, the so-called ‘delamination’ layer, and the spreader mesh sheet are removed and the component is separated from the mould. The infusion process is very simple in its concept, but requires detailed planning and design [12, 15] and a range of auxiliary materials (lost during the process), making it more costly. The infusion rate depends upon the viscosity of the resin [19], the distance the resin and the hardener flow in the mould, the permeability of the pieces (especially of the reinforcement fabric) and the negative pressure value. In the research presented in this article, attention was focused on the latter factor in an attempt to determine the effect of negative pressure values on the properties (mainly mechanical ones) of the carbon fibre-reinforced composite.

Carbon fibres play a key role in various specialised applications such as aerospace and general engineering due to their low weight-to-strength, high unit strength and stiffness, dimensional stability, low coefficient of thermal expansion, fatigue and creep resistance, as well as good thermal and electrical conductivity [4, 7]. These fibres are widely used in the form of woven textiles, prepregs, continuous filaments and staple fibres. Carbon fibre-reinforced composite materials are commonly used in aircraft structures, e.g. for the construction of fuselages, wings, horizontal or vertical stabilisers [9, 10, 11].

PREPARATION OF TEST MATERIALS

STYLE E 452, a 200 g/m^2 carbon fibre fabric with twill weave was used to manufacture the 400x700 mm composite panels. The laminate consisted of nine layers [2, 7]. The matrix of the examined composites was epoxy mixture resin L285 with H287 hardener [20], mixed in a ratio of 100: 40. The prepared composite material was vented using a negative pressure pump to remove unwanted air bubbles [18]. The composites were assembled and fabricated on a glass plate (Fig. 1), coated with TR Industries 104 wax. For the purpose of the research, three composite panels were manufactured with the same technology. The panels differed only in the value of the applied negative pressure: -0.4 bar, -0.7 bar and -1.0 bar. The manufacture of laminates was carried out according to the technology described in the available literature. In the final step, after the negative pressure bag was closed and the lines were connected to the mould to the liquid matrix tank and the negative pressure pump, the valves located on the above-mentioned lines were opened, causing the resin composition to seep through the previously laid reinforcement layers (Fig. 1). Once this process was finished (the mould was completely filled with the liquid matrix), the resin-hardener supply valve was closed. After 24 hours when the material was fully cured, the composite plate was removed from the mould.

RESEARCH RESULTS

A set of samples was cut from the fabricated composite panels using a water jet cutting machine for testing the mechanical properties: tensile strength, flexural strength and impact strength. Before the samples were subjected to strength testing, they were subjected to an assessment of surface quality and internal structure. Also weight measurements were taken. The thickness of the laminates produced with 0.4 bar and 0.7 bar negative pressures was approximately 2.5 mm (Fig. 2) and their averaged surface weight equalled approximately 3.3 kg/m^2 (reinforcement to total laminate weight content was approximately 55%). The thickness of the laminate produced at 1.0 bar negative pressure was approximately 1.9 mm and the surface mass was 2.6 kg/m^2 (reinforcement content by weight to total laminate mass was approximately 70%). During the manufacture of the laminates, the time for the resin composition to seep through the reinforcement material was also measured - for composites manufactured at negative pressures of 0.4 and 0.7 bar, this time was approximately 50 minutes, whereas for negative pressures of 1.0 bar, approximately 40 minutes. Figures 3-8 show microscopic images of the surface of the laminates and sections of their internal structure taken with a TAGARNO TREND HD digital microscope.

Analysis of the internal structure of the laminates (Figures 4, 6, 8), apart from tighter reinforcing layers (related to the decreasing thickness of the laminate along with increasing negative pressure values), showed no significant differences for any of the materials (the occurrence of the so-called ‘voids’ [14] for each laminate in similar numbers was noted - these were due to the presence of air bubbles in the resin/hardener

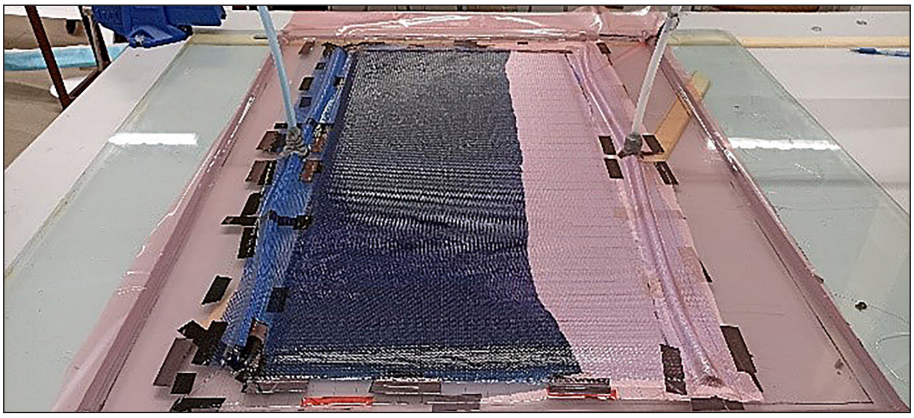

Fig. 1. Fabrication of a composite panel using the infusion method

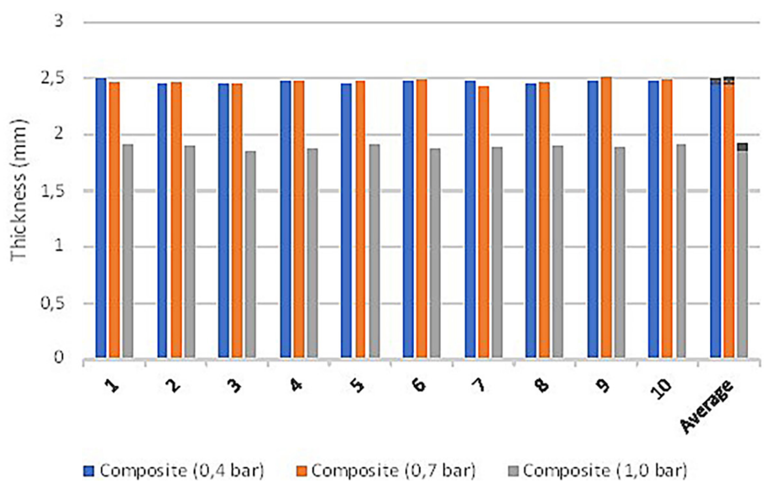

Fig. 2. Thickness of laminates with standard deviation

Fig. 3. Laminate surface made at a negative pressure of 0.4 bar

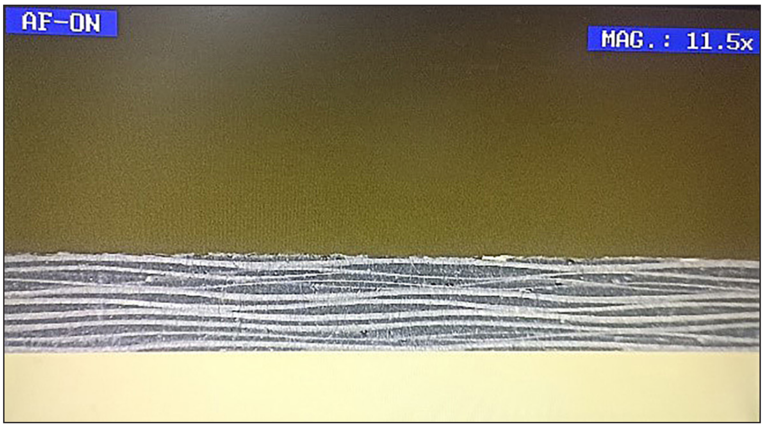

Fig. 4. Internal structure of a laminate made with a negative pressure of 0.4 bar

Fig. 5. Laminate surface made at a negative pressure of 0.7 bar

composition, introduced into it during the mixing of the two components). An analysis of the external structure (the surface of the laminates, especially the smooth surface formed on the glass side during laminate manufacture) shows that the highest surface quality was obtained in the composite manufactured at a negative pressure of 0.7 bar (there are isolated cases of surface 'voids' - Fig. 5). A lower surface quality was characteristic of the laminate produced at 0.4 bar negative pressure (higher number of surface 'voids', particularly in the areas where the fibre strands of the reinforcement material crossed over - Fig. 3). The composite produced at a negative pressure of 1.0 bar was characterised by the worst surface texture (Fig. 7) with visible matrix deficiencies throughout the laminate in areas of crossing carbon fibre strands. An analysis of the structure and weight of

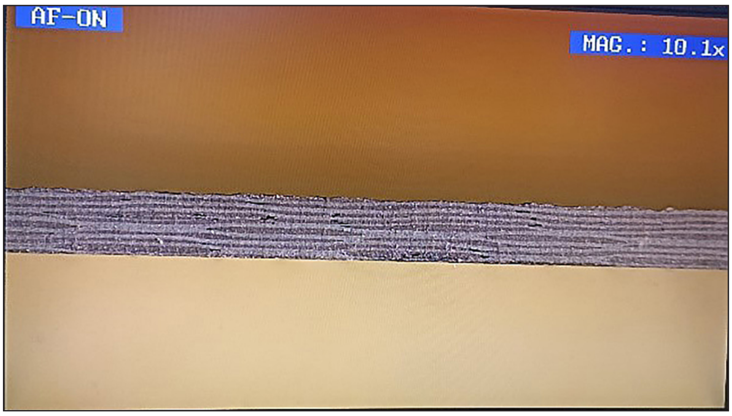

Fig. 6. Internal structure of a laminate made with a negative pressure of 0.7 bar

Fig. 7. Laminate surface made at a negative pressure of 1.0 bar

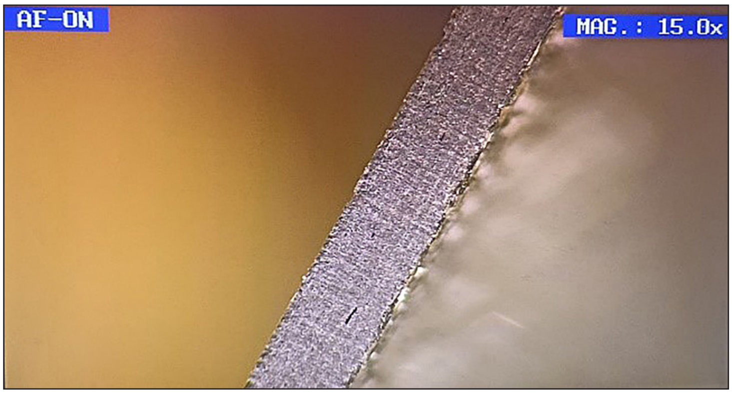

Fig. 8. Internal structure of a laminate made with a negative pressure of 1.0 bar

the laminates shows that the materials produced at 0.4 bar and 0.7 bar negative pressures have similar properties, while the material produced with 1.0 bar negative pressure has the best properties (lowest thickness and weight), which is particularly desirable for aerospace applications. However, due to the imperfections in the outer structure of the material made at the maximum negative pressure value, it is worth carrying out environmental tests to assess whether imperfections in the surface layer will adversely affect the properties of the composite in long-term use.

IMPACT TEST

The test was conducted to determine the impact strength of the composite [6], under surface and edge loading. An SW-5 impact hammer with a pendulum with a maximum energy of 50 J was used for the test. Sixty 10 × 80 mm samples were tested (20 pieces of each laminate: 10 samples from each laminate were surface tested and 10 samples were edge tested). The results from the surveys are shown in the graphs (Figures 9, 10). After analysing the impact strength, it can be concluded (for both surface and edge impact strength) that the materials made at 0.4 and 0.7 bar negative

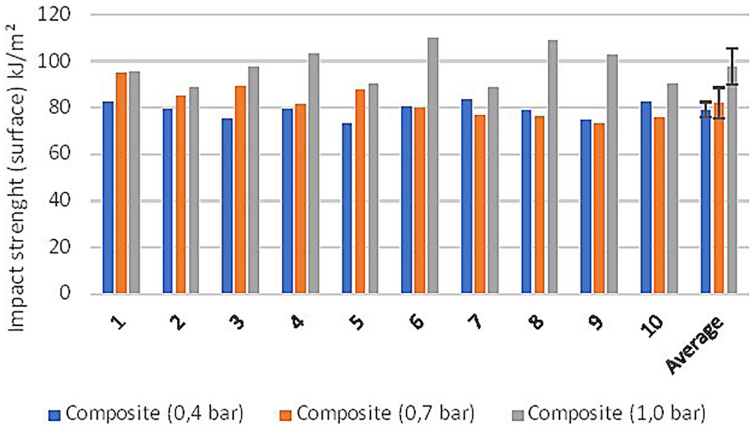

Fig. 9. Surface impact strength of tested materials with standard deviation

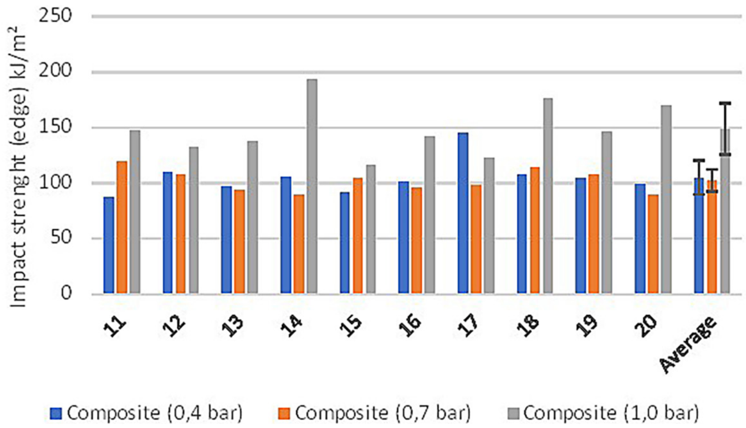

Fig. 10. Edge impact strength of tested materials with standard deviation

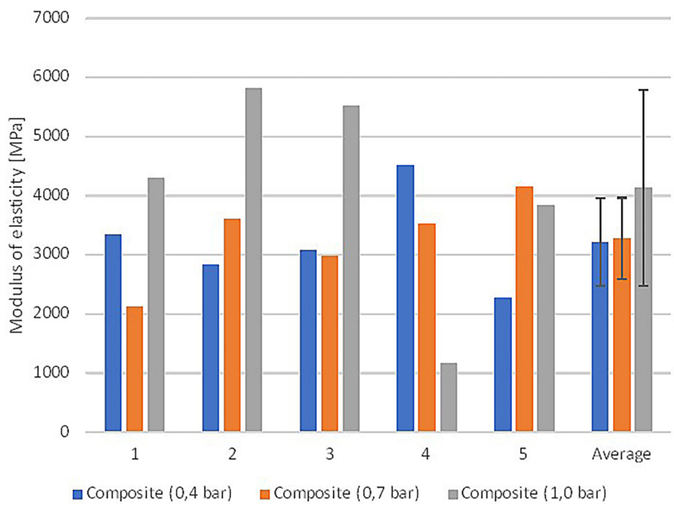

Fig. 11. Longitudinal modulus of elasticity of materials during tensile testing with standard deviation

pressure have similar impact strength values (Figures 9, 10). The impact strength of the composite made at the highest negative pressure value was 40% higher at edge loading and 20% higher at surface loading, as opposed to the other materials.

Static tensile test

A Zwick/Roell Z100 universal testing machine was used for the test. The test was conducted in accordance with the PN-EN ISO 527-5 standard. Fifteen samples were tested (the batch size for each manufactured laminate was 5). In the experiment, the authors used T-bone shaped samples. The findings of the tests are presented in diagrams (Figures 11, 12). As in the impact test, the results of the tensile test of the composite made at the highest negative pressure (1.0 bar) were more than 20% higher (longitudinal modulus and tensile strength) compared to materials made at low and medium negative pressures (0.4 and 0.7 bar). It is also worth noting that, in addition to the best tensile test results of the composite produced at the highest negative pressure value, these results also had the smallest deviations from the mean value.

Bend test

Five samples from each laminate, measuring 60 × 80 mm and freely lying on sliding supports with 60 mm spacing, were tested. The test was carried on a Zwick/Roell 5kN universal testing machine, in accordance with the bending scheme of method A (three-point bending) described in

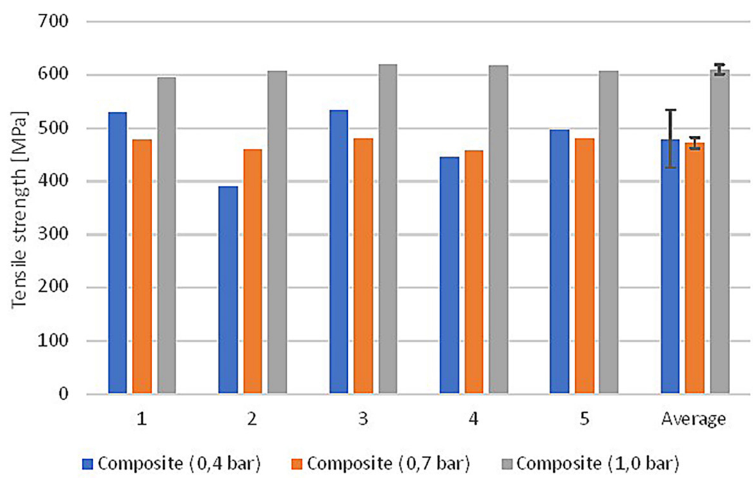

Fig. 12. Tensile strengths of tested materials with standard deviation

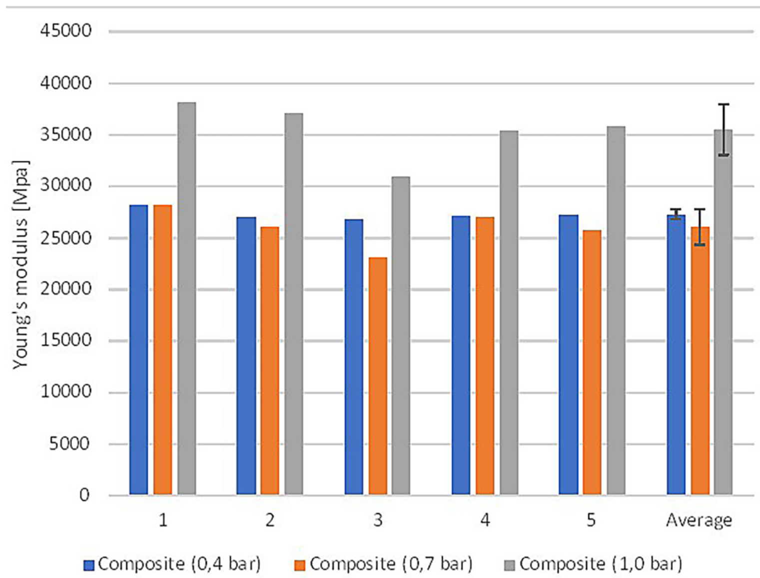

Fig. 13. Young's modulus of materials during three-point bending test with standard deviation

PN-EN ISO 14125, with the results shown in the presented diagrams (Figures 13 and 14). The flexural strengths of all the materials tested are similar (Fig. 14). The value of Young's modulus in the three-point bending test of the material made at the maximum negative pressure, as in other tests, was more than 20% higher than that of materials made at lower negative pressures (Figure 13).

Penetration test

Another test to which the 60 x 80 mm samples were subjected was the puncture resistance test. An Instron Ceast 9340 drop hammer (Fig. 15) was used, allowing analyses to be carried out with energies ranging from 0.20 – 405 J. In the tests performed, the samples (5 pieces each) were loaded with energies successively: 5 J; 10 J; and the energy causing the sample to separate (for the composite made at 0.4 bar negative pressure it was – 14 J, for the composite made at 0.7 bar negative pressure – 15 J, and for the composite made at 1.0 bar negative pressure – 20 J). A total of 15 samples from each laminate were tested. After the puncture test, the samples were subjected to a flexural test to determine the residual flexural strength and Young's modulus. The graphs (Figures 16-21) show the results of

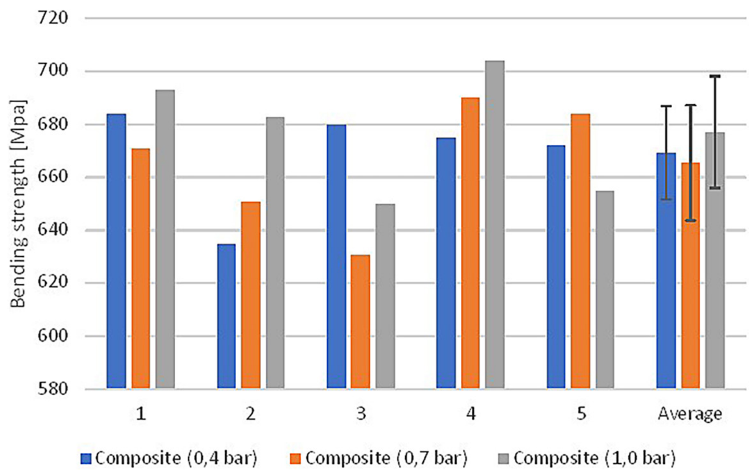

Fig. 14. Flexural strength of the tested materials with standard deviation

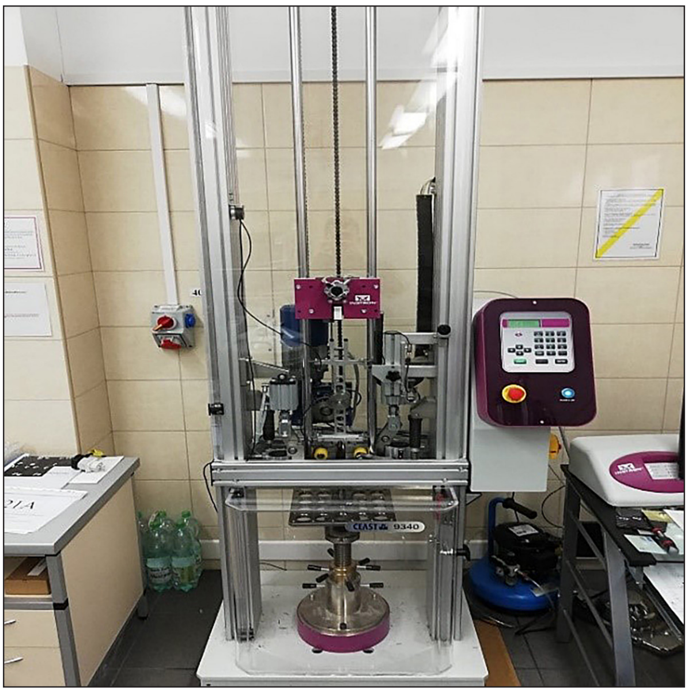

Fig. 15. Instron Ceast 9340 drop hammer

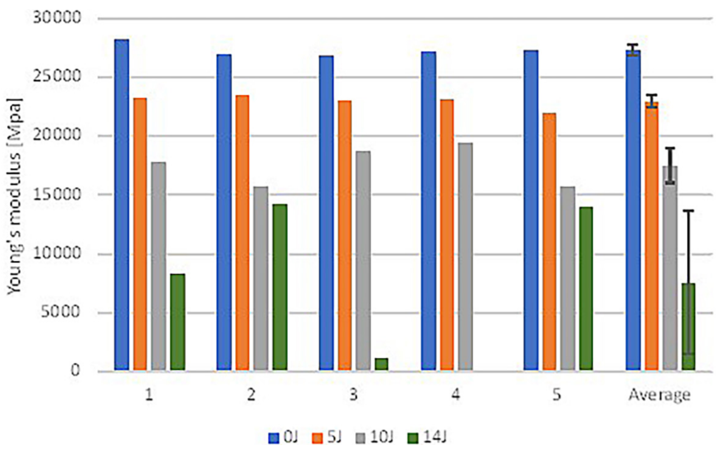

Fig. 16. Young's modulus of the composite (0.4 bar) after impact loading with standard deviation

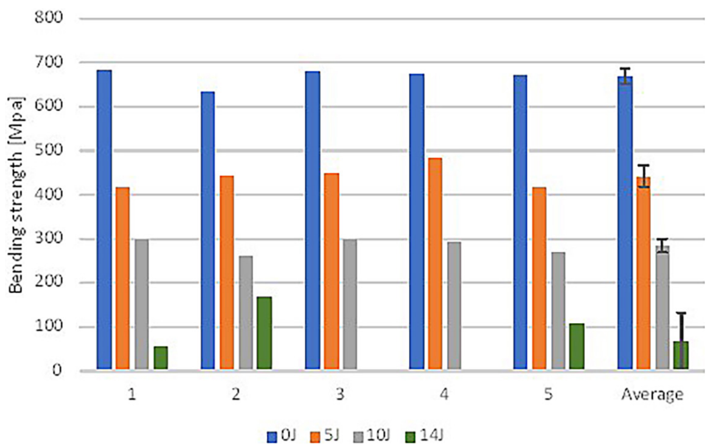

Fig. 17. Bending strength of the composite (0.4 bar) after impact loading with standard deviation

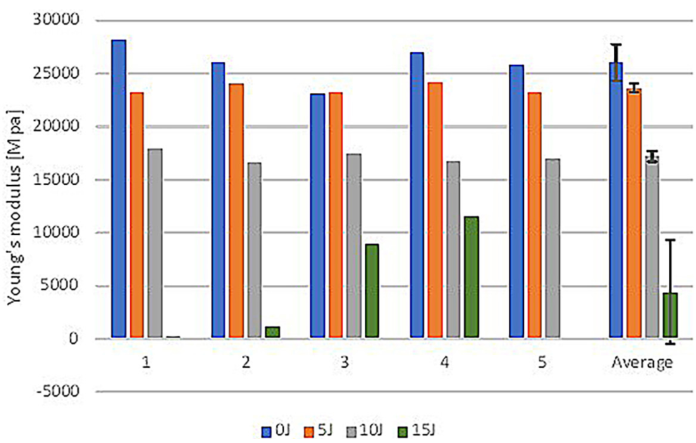

Fig. 18. Young's modulus of the composite (0.7 bar) after impact loading with standard deviation

this test - the results obtained in the bending test of the composites not subjected to the puncture test have been added to the graphs – denoted as 0 J.

After an analysis of the results of the material puncture test and subsequent bending tests, it was again found that the best properties were obtained for the material made at a negative pressure of 1.0 bar. This material obtains the highest values of the analysed coefficients for the puncture test with each energy, and also the distribution of the results and the decrease in strength and Young's modulus when it is loaded with successive

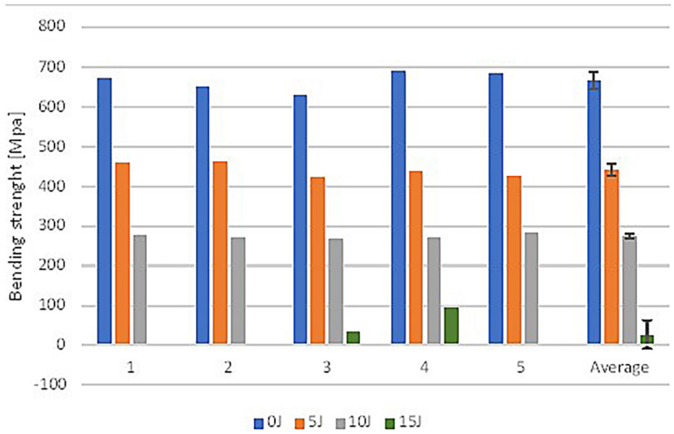

Fig. 19. Bending strength of the composite (0.7 bar) after impact loading with standard deviation

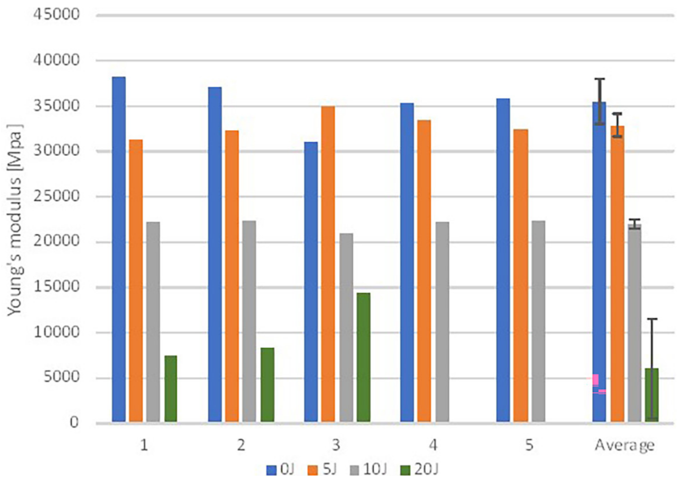

Fig. 20. Young's modulus of the composite (1.0 bar) after impact loading with standard deviation

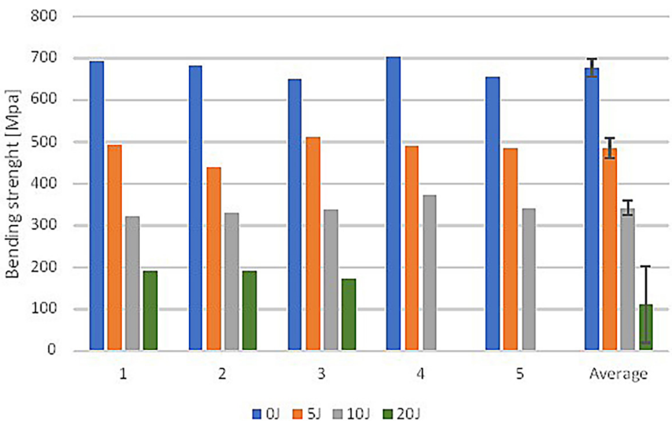

Fig. 21. Composite strength (1.0 bar) after impact loading with standard deviation

energies appears to be the most uniform and predictable. It should also be noted that, despite the impact loading of the composite produced at a negative pressure of 1 bar with an energy of 20 J, its parameters obtained during the estimation of residual bending strength were found to be better than the other composites, which were loaded with lower energies (14 J and 15 J). It appears that the material made at 1.0 bar negative pressure shows the best characteristics in terms of strength because in this material the average distances between each of the nine composite layers are the smallest (preventing a large number of air bubbles from remaining inside the material) and the percentage ratio of reinforcement to total composite weight is the highest (~70%) in this material.

CONCLUSIONS

On the basis on the conducted investigations it was found that the best performance characteristics (the lowest weight and thickness – especially important in aircraft structures) are found in the material produced at the highest negative pressure value (1,0 bar). The best aesthetic properties (surface quality) are obtained with a laminate produced at an intermediate negative pressure value (0.7 bar) – visual inspection [18, 21]. All the mechanical properties of the composite produced at the highest negative pressure value are clearly the best among the materials tested.

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