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THE INFLUENCE OF MANUFACTURING TECHNOLOGY ON THE MECHANICAL PROPERTIES OF THE LAYERED COMPOSITE

WPŁYW METODY WYTWARZANIA KOMPOZYTU WARSTWOWEGO NA JEGO WŁAŚCIWOŚCI MECHANICZNE

Abstract

The share of composites in today's aerospace industry is steadily increasing. Layered composites are the most popular in aviation. There are a number of methods of their manufacture, each with specific characteristics. One of the most popular simple methods are the technique using a hydraulic press to apply pressure, the vacuum bag method and the infusion method. They are all widely used and useful in individual and mass production, and allow the same types of composites to be made, but due to the differences, the resulting composites, despite having the same structure, may have different properties. In order to verify this observation, an experimental

Streszczenie

Udział kompozytów we współczesnym przemyśle lotniczym stale wzrasta. Największą popularnością w lotnictwie cieszą się kompozyty warstwowe. Istnieje wiele metod ich wytwarzania, z których każda cechuje się określonymi właściwościami. Najpopularniejsze z prostych metod to: technika wykorzystująca prasę hydrauliczną do wywarcia nacisku, metoda worka próżniowego oraz metoda infuzji. Wszystkie są powszechnie stosowane i użyteczne w produkcji jednostkowej i seryjnej oraz umożliwiają wykonywanie takich samych typów kompozytów, jednak ze względu na różnice, uzyskane kompozyty pomimo takiej samej struktury mogą mieć różne

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study of the same carbon fabric-reinforced polymer layered composites made by the methods mentioned above was carried out. The mechanical properties of the composites were studied, with a particular focus on their resistance to low-energy impact loading. The results of the study indicate that the composites produced by the infusion method have the best mechanical properties, and with the selected manufacturing technology parameters, the method using a hydraulic press produced the composite with the lowest surface mass.

Keywords: polymer layered, composites, method of manufacture, experimental testinge

właściwości. Celem weryfikacji tego spostrzeżenia przeprowadzono badania eksperymentalne takich samych polimerowych kompozytów warstwowych wzmacnianych tkaniną węglową, wykonanych wymienionymi metodami. Badano właściwości mechaniczne kompozytów, ze szczególnym uwzględnieniem ich odporności na niskoenergetyczne obciążenia udarowe. Wyniki badań wskazują, że kompozyty wytworzone metodą infuzji cechują się najlepszymi właściwościami mechanicznymi, a przy zastosowaniu wybranych parametrów technologii wytwarzania, metoda wykorzystująca prasę hydrauliczną umożliwiła wytworzenie kompozytu o najmniejszej masie powierzchniowej.

Słowa kluczowe: kompozyty warstwowe, polimerowe, sposób wytwarzania, badania eksperymentalne

1. INTRODUCTION

The share of composites in today's aerospace industry is steadily increasing[1]. The unique properties of composite materials determine their selection as basic materials for use in aerospace structures[2]. Layered composites are the most popular in aviation[3]. There are a number of methods for producing them, each with specific characteristics[4].

The infusion technique is one of the most innovative and fastest growing methods for producing strong and lightweight laminates[5]. The process is based on laying dry reinforcement (e.g. roving mats) into a mould with a pre-applied gelcoat, laying the delamination and installing the resin spreading system. The mould prepared in such as manner is then sealed with a vacuum bag and an apparatus is connected to the injection points to supply the resin previously mixed with a hardener. The biggest

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2 Krzyżak A., Mazur M., Gajewski M., Drozd K., Komorek A., Przybyłek P., Sandwich structured composites for aeronautics: methods of manufacturing affecting some mechanical properties. International Journal of Aerospace Engineering, 2016; Godzimirski J., Materiały lotnicze, WAT, Warszawa 2008; Wilczyński A.P., Polimerowe kompozyty włókniste, Wydawnictwa Naukowo-Techniczne, Warszawa 1996; Staszewski W., Boller Ch., Tomlinson G., Health Monitoring of Aerospace Structures. John Willey & Sons, Ltd, 2004.

3 Boczkowska A., Kapuściński J., Puciłkowski K., Wojciechowski S., Kompozyty, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2000.

4 Kesarwani P., Jahan S., Kesarwani K., Composites: Classification and its manufacturing proces, International Journal of Applied Research, 2015; Ochelski S., Metody doświadczalne mechaniki kompozytów konstrukcyjnych, Wydawnictwa Naukowo-Techniczne, Warszawa 2004; Konsztowicz K., Kompozyty wzmacniane włóknami. Podstawy technologii, Wydawnictwo AGH, Kraków 1986.

5 Balasubramanian K., Mohamed TH Sultan, Rajeswari N., Manufacturing techniques of composites for aerospace applications. Sustainable composites for aerospace applications. Woodhead Publishing, 2018; Heng H., Belouettar S., Potier-Ferry M., Review and assessment of various theories for modeling sandwich composites. Composite Structures 84(3), 2008.

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advantage of manufacturing laminates by infusion is its low cost and lack of complexity of the process[6].

The vacuum bag composite method uses atmospheric pressure as a medium to maintain pressure until the resin cures. The process combines elements of the contact technique (manual fibre seepage) with vacuum forming. In practice, successive reinforcing layers are drenched with resin mixed with a hardener, followed by a layer of a delamination fabric, and a drainage fabric. The semi-finished product, prepared in such a manner, is sealed in a vacuum bag to which an air extraction system is connected. Extraction of the air and maintaining a constant vacuum allows the atmospheric air to surround the bag from the outside to exert pressure evenly over the entire laminate surface.

The method using a hydraulic press enables very good reinforcement to matrix ratio to be achieved. Most often, the process of producing a composite using this method is carried out by placing suitably saturated layers of reinforcement in a mould and pressing under sufficiently high pressure[7]. In addition, moulds equipped with heating systems and venting channels are very often used to improve the product quality. The hydraulic press enables a highly accurate and efficient production of composites. The quality of the products obtained with this method predestines it for series production[8]. Furthermore, it also provides the possibility of repairing composite structures, making it a method of wide application.

In the experimental study, it was decided to evaluate the properties of the composites produced by the three methods mentioned above with a particular focus on the resistance of these materials to low-energy impact loads.

2. RESEARCH METHODS

2.1. MANUFACTURE OF A COMPOSITE BY THE VACUUM BAG METHOD

Composites made by means of the vacuum bag method STYLE E 452, a 200 g/m^2 carbon fibre fabric with twill weave, was used to manufacture the 400 x 700 mm composite panels. The laminate consisted of seven layers. The laid carbon fabrics were manually drenched with L285 epoxy resin mixed with H287 hardener at a weight ratio of 100:40. In an effort to achieve the best possible mechanical properties for the manufactured composites, the resin/hardener mixture was vented using a vacuum pump, which allowed air bubbles to be removed from the mixture. After eight hours required for the resin to cure, the bag was opened and the manufactured laminate was removed. The average thickness of the composite was approximately 2 mm, and the weight of the sample (a 10 mm wide, 150 mm long ‘paddle’ shape) was 5.16 g.

6 Ehrenstein G.W., Fasserverbund-Kunsttoffe, Hanser Verlag, München 2006.

7 Palmer R.J., History of composites in aeronautics. Wiley, Encyclopedia of Composites (2011); Goraj Z., Struktury kompozytowe w lotnictwie. Prace Naukowe Politechniki Warszawskiej. Mechanika 219 (2007).

8 Karpowicz A.S., Metody wytwarzania kompozytowych struktur płatowca. Diss. Instytut Techniki Lotniczej i Mechaniki Stosowanej, 2016.

2.2. MANUFACTURE OF A COMPOSITE BY THE INFUSION METHOD

STYLE E 452 carbon fibre fabric was also used to create the composite by infusion. The laminate consisted of seven layers. The production process differed significantly from the other methods. The composites were assembled and fabricated on a glass plate, coated with TR Industries 104 wax. The advantage of the infusion method implemented in this way is that composites of any size and shape can be created, unlimited by the size of the press or a vacuum bag. A mixture of L285 resin and H287 hardener was prepared in a 100:40 ratio. The process of mixing the hardener together with the resin took 2 minutes and the gel and build-up time for a 1 mm layer at 26°C was approximately 6-8 hours. The prepared mixture was vented using a vacuum pump to remove unwanted air bubbles. After the required eight hours for the resin to cure, the manufactured laminate was removed from the bag. The composite was produced using a vacuum of approximately -0.8 bar. The average thickness of the composite was approximately 2 mm, and the weight of the sample (a 10 mm wide, 150 mm long 'paddle' shape) was 5.16 g.

2.3. COMPOSITE MADE BY MEANS OF A HYDRAULIC PRESS

The manufacture of composites using the hydraulic press method is one of the primary ways of producing laminates. The presses allow huge pressures to be achieved by exploiting Pascal's law. The press force acts uniformly on the entire surface of the composite parts to be cured.

A mixture of L285 resin and H287 hardener was prepared in a 100:40 ratio. In an effort to achieve the best possible mechanical properties for the produced composites, the resin/hardener mixture was ventilated using a vacuum pump, which allowed air bubbles to be removed from the mixture. The percolation of successive layers was done by hand using a velour roller.

The resin-soaked carbon fibre layers were encapsulated between two sheets of PET film, the edges of which were taped to collect excess resin. The laminate prepared, in such a way, was placed in the press and a load of 30 tonnes was applied. After 24 hours, the laminate was removed from the press and visually inspected. The average thickness of the composite was approximately 2 mm, and the weight of the sample (a 10 mm wide, 150 mm long 'paddle' shape) was 5.16 g.

3. TESTING THE MECHANICAL PROPERTIES OF COMPOSITES

3.1. BENDING TESTING

A flexural strength test was chosen as a primary test, which, in addition to determining Young's modulus in bending and flexural strength, was used to assess the effect of low-energy impact loads on the fabricated composites. A series of five 60 x 80 mm samples lying freely on sliding supports, spaced 64 mm apart, were

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subjected to bending tests. The test was carried out using a Zwick/Roell 5kN universal testing machine, in accordance with the bending scheme of method A (three--compression bending) described in EN ISO 14125, with the results shown in the diagrams (Figures 1 and 2).

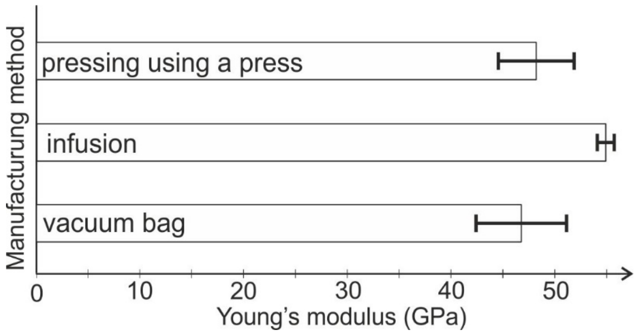

Fig. 1. Young's modulus of the tested composites
Source: own study.

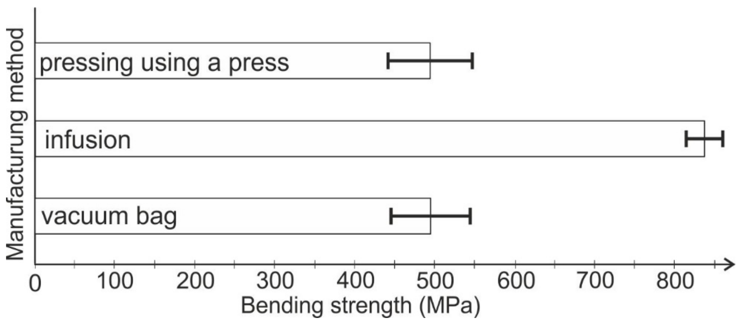

Fig. 2. Flexural strength of the tested composites
Source: own study.

3.2. EXAMINING THE INFLUENCE OF LOW ENERGY LOADS ON COMPOSITES

Another test to which the 60 x 80 mm samples were subjected was the puncture resistance test. The test used an INSTRON CEAST 9340 drop hammer and the samples were loaded with energies of 3 J; 5 J; 10 J; 15 J; 20 J. The authors used a spherical impactor with a diameter of 20 mm. The number of each examined series was equal to 3.

The 3 J energy did not damage the structure of the composite produced by the vacuum bag method, causing an average indentation of 0.11 mm. (Figure 3a).

(a) (b) (c)

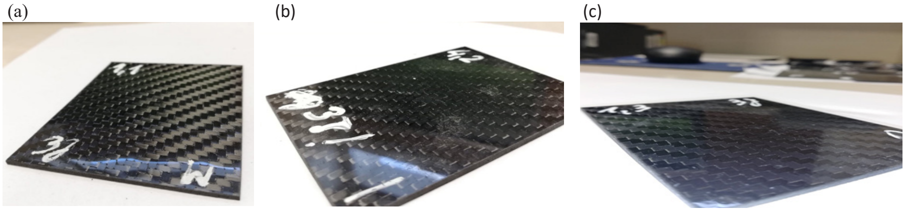

Fig. 3. Visual assessment of damage to samples loaded with 3 J, (a) vacuum bag method, (b) infusion method, (c) method of fabrication using a hydraulic press

Source: own study.

Loading the composites produced by the infusion method and the 3 J press method did not damage the structure of the composites, but only caused visible indentations of the surface layer with a depth of 0.09 mm (infusion) (Fig. 3b) and with a depth of 0.14 mm (hydraulic press method) (Fig. 3c).

The 5 J energy did not damage the structure of any of the composites, and the average indentation at the point of load application equalled 0.28 mm (Fig. 4a) (vacuum bag), 0.25 mm (infusion) and 0.31 mm (pressing).

(a) (b) (c)

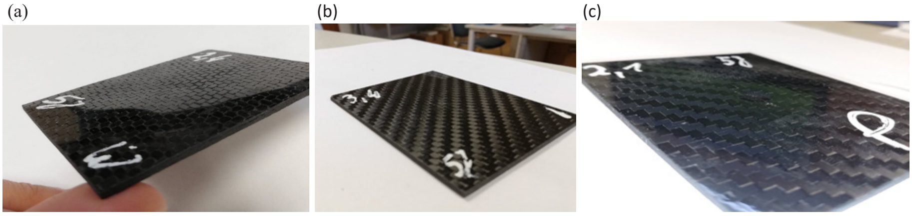

Fig. 4. Visual assessment of damage to samples loaded with 5 J, (a) vacuum bag method, (b) infusion method, (c) method of fabrication using a press

Source: own study.

An energy of 10 J caused deformation and fracture of the composite layers propagating in four directions, with an average indentation of 0.45 mm (Fig. 5a) (vacuum bag). An energy of 10 J resulted in a fracture of the composite structure and an average indentation of 0.41 mm (Fig. 5b) (infusion).

(a) (b) (c)

Fig. 5. Visual assessment of damage to samples loaded with 10 J, (a) vacuum bag method, (b) infusion method, (c) method of fabrication using a press

Source: own study.

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An energy of 10 J caused the composite layers to deform and fracture, with an average indentation of 0.49 mm (Fig. 5c) (press).

An energy load of 15 J caused a large indentation with an average value of 0.93 mm and fracture of all laminate layers (Fig. 6a) (vacuum bag).

(a) (b) (c)

Fig. 6. Visual assessment of damage to samples loaded with 15 J, (a) vacuum bag method, (b) infusion method, (c) method of fabrication using a press hydraulic

Source: own study.

An energy of 15 J resulted in a fracture of the composite layer and a large indentation of 0.81 mm (Fig. 6b) (infusion).

An energy load of 15 J caused a large indentation with an average value of 1.02 mm and fracture of all laminate layers (Fig. 6c) (press).

At a load of 20 J, it was possible to observe complete piercing of the test samples and fracture of the composite structure along its entire length (Fig. 7) (vacuum bag).

(a) (b) (c)

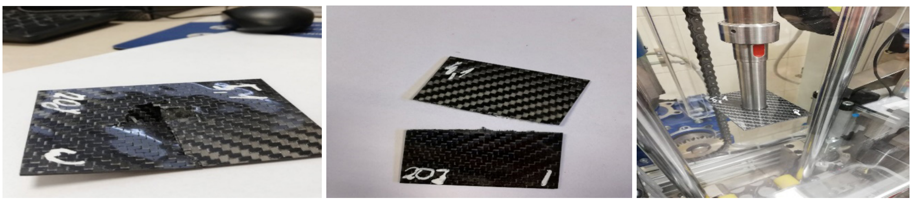

Fig. 7. Visual assessment of damage to samples loaded with 20 J, (a) vacuum bag method, (b) infusion method, (c) method of fabrication using a press

Source: own study.

An impact with an energy of 20 J led to a complete destruction of the composite and separation into two parts (Fig. 7b) (infusion). At a load of 20 J, complete penetration of the test sample was observed (Fig. 7c) (press).

3.3. POST-IMPACT FLEXURAL STRENGTH TESTING (RESIDUAL STRENGTH TESTING)

After the puncture test, the samples were subjected to a flexural test to determine the residual flexural strength and Young's modulus of the composite formed in the vacuum bag. The obtained results have been presented in Figures 8 and 9.

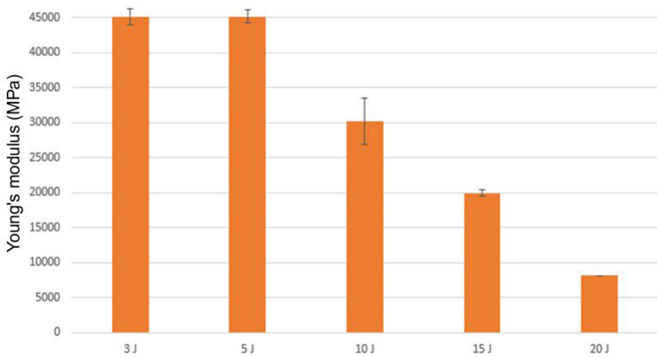

Fig. 8. Mean values of Young's modulus of composites made with the vacuum bag method after impact tests

Source: own study.

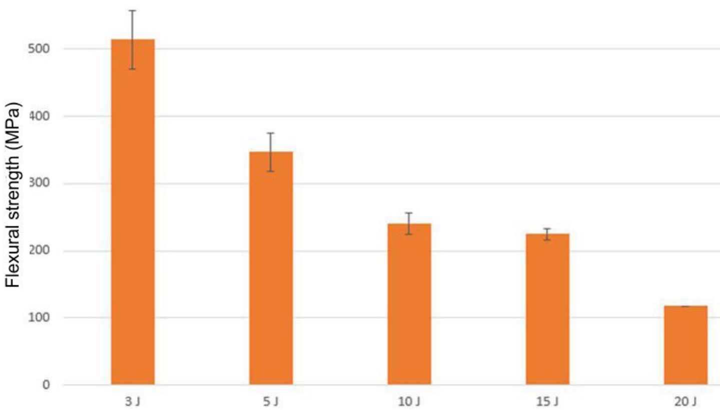

Fig. 9. Average flexural strength values of composites made with the vacuum bag method after impact tests

Source: own study.

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A load of 3 J resulted in a decrease of approximately 3 GPa in Young's modulus, while flexural strength was not affected. At an energy of 5 J, the Young's modulus is observed to remain at the same level as for an impact with an energy of 3 J, while a decrease in flexural strength of 150 MPa is apparent. A load of 10 J significantly reduced the Young's modulus by 18 GPa and the flexural strength dropped by 250 MPa. At an energy of 15 J, the composite was significantly damaged by which its Young's modulus decreased by 28 GPa and its flexural strength by 270 MPa. The impact with an energy of 20 J caused the composite to completely crack and fracture over its entire surface, causing the Young's modulus to decrease by 51 GPa and the flexural strength to decrease by 380 MPa.

The composites manufactured with the infusion method were also re-examined for their residual flexural strength. The obtained results have been presented in Figures 10 and 11.

The flexural strength of the composite manufactured with the infusion method deteriorated by 150 MPa after impact loading with an energy of 3 J, while Young's modulus decreased by 1 GPa. A load of 5 J resulted in a decrease in flexural strength and Young's modulus of 230 MPa and 6 GPa, respectively. At an impact energy of 10 J, at which the composite structure was clearly fractured, the flexural strength and Young's modulus values deteriorated by 390 MPa, and by 27 GPa. A loading energy of 15 J caused all layers of the composite to fracture, resulting in a decrease of 35 GPa in Young's modulus and 590 MPa in flexural strength. The impact with an energy of 20 J caused the composite to be completely destroyed and split into two parts.

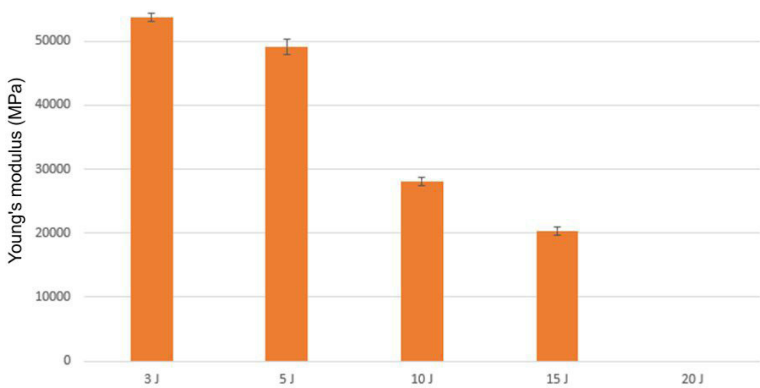

Fig. 10. Mean values of Young's modulus of composites made by the infusion method after impact tests

Source: own study.

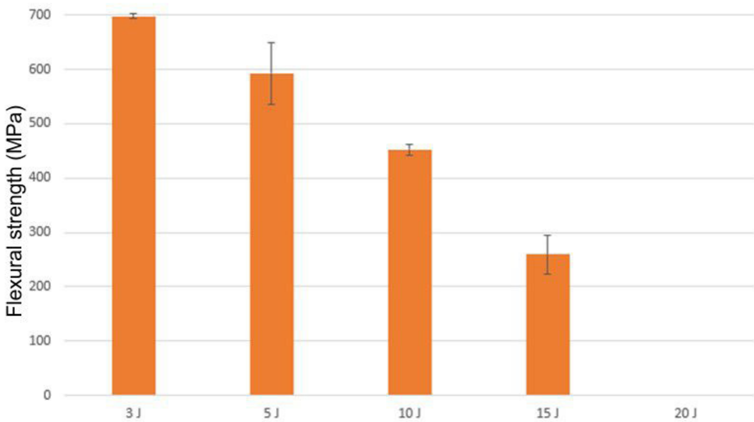

Fig. 11. Average flexural strength values of composites made by the infusion method after impact tests

Source: own study.

After the puncture test, the compression-moulded composite samples were subjected to a flexural test in order to determine the residual flexural strength. The obtained results have been presented in Figures 12 and 13.

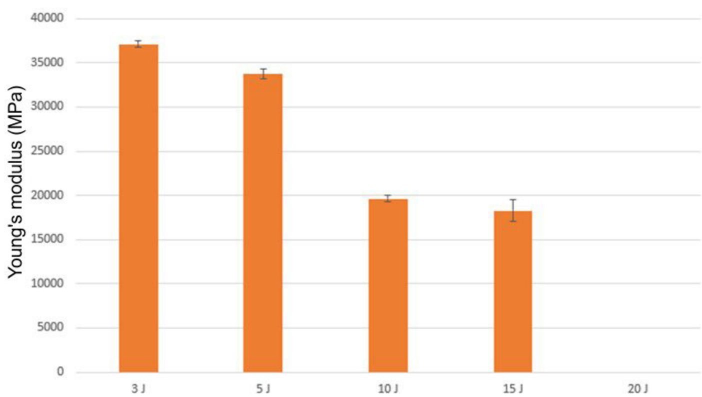

Fig. 12. Mean value of Young's modulus of composites made by compression moulding after impact tests

Source: own study.

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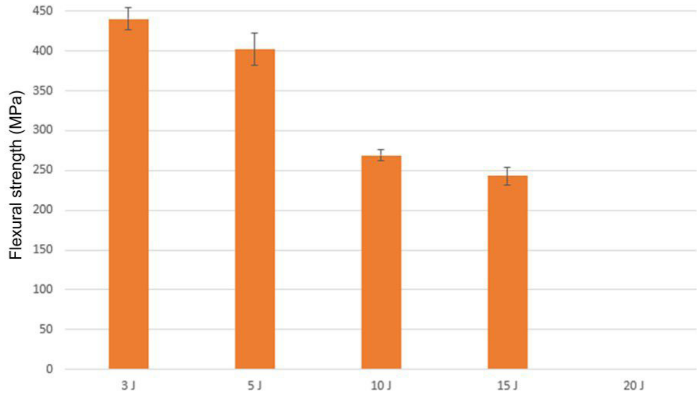

Fig. 13. Average flexural strength values of composites made by the vacuum bag method after impact tests
Source: own study.

The load of 3 J caused a decrease in the Young's modulus by 9 GPa and in the flexural strength by 40 MPa. At an energy of 5 J, it is possible to observe a decrease in Young's modulus of 14 GPa and a decrease in flexural strength of 80 MPa. A load of 10 J significantly reduced the Young's modulus by 19 GPa and the flexural strength dropped by 220 MPa. At an energy of 15 J, the composite was significantly damaged, thus its Young's modulus decreased by 21 GPa and its flexural strength by 240 MPa. The impact with an energy of 20 J caused the composite to completely break and fracture over its entire surface, making it unsuitable for further testing.

3.4. TENSILE TESTING

The next test to which the fabricated composite samples were subjected was the tensile test. The number of samples in the batch equalled five. The speed of the traverse movement equalled 2 mm/min. The obtained results are shown in the graph (Fig. 14).

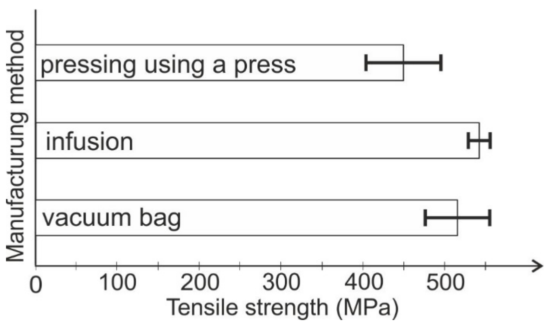

Fig. 14. Tensile strength of the tested composites
Source: own study.

The tensile strength of all the tested materials was similar. It is worthwhile stressing that the composite made with the infusion method had the highest average tensile strength, and the small scatter in the results indicates good structural homogeneity of the composite made with this method.

3.5. IMPACT STRENGTH TESTING

Another test was the determination of impact strength using a Galdabini Impact 25 pendulum hammer. The impact strength was determined when the sample was edge loaded (Fig. 15) as well as plane loaded (Fig. 16).

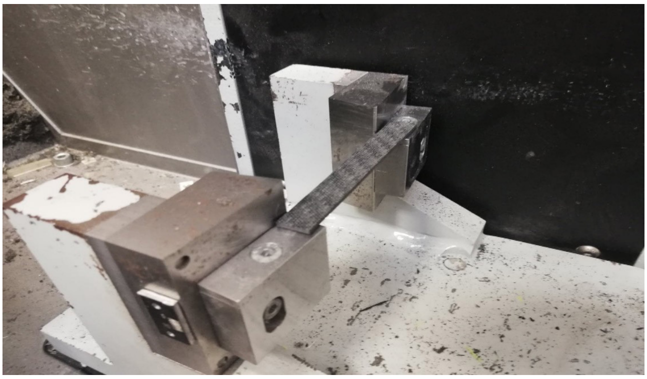

Fig. 15. Edge loaded sample
Source: own study.

Fig. 16. Plane loaded sample
Source: own study.

The results obtained are presented in the form of graphs (Fig. 17–18).

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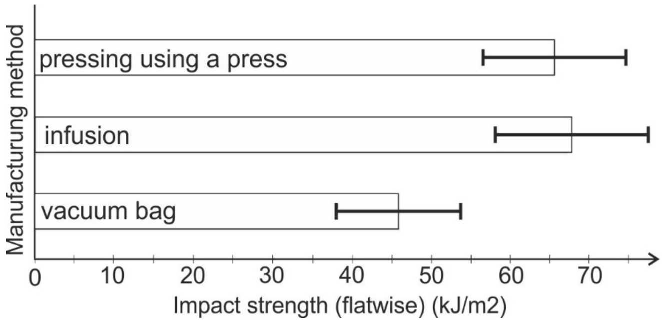

Fig. 17. Impact strength of plane-loaded samples
Source: own study.

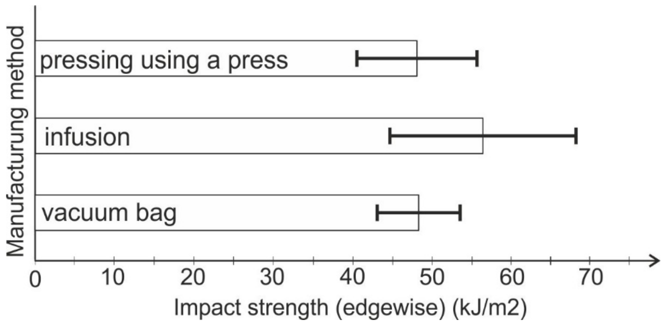

Fig. 18. Impact strength of edge loaded samples
Source: own study.

The scatter of impact test results was large for all composites, regardless of the method of load application. In the case of plane loading, the impact strength of the composite made by the vacuum bag method was more than 20 % less than that of composites made by the other methods.

4. COMPARISON OF THE PROPERTIES OF THE MANUFACTURED COMPOSITES

The used methods varied in preparation time, difficulty of execution and the amount of the materials used.

Due to the time required to prepare the composite, the method that allowed the fastest production was the vacuum bag technique. The hydraulic press method required slightly more time, while the infusion method involved the greatest time investment due to the preparation of the entire apparatus.

As indicated by the results of strength tests of composites produced by the following methods: vacuum bag, infusion, hydraulic press, the composites produced by the infusion method were characterised by higher mechanical strength in almost all the performed tests. The average Young's modulus at bending for the infused composites was 55 GPa, while the average flexural strength was 840 MPa. Compared to the composites formed in the vacuum bag, the average Young's modulus was 15 % lower at 47 GPa, while the average flexural strength was 490 MPa, 42 % lower. Similar differences were observed when comparing the infusion to the hydraulic press, where the Young's modulus was 13 % lower at 48 GPa and the average flexural strength was equal to the value obtained in the composite produced by the vacuum bag method and was the same at 490 MPa.

The average modulus of elasticity determined during the static tensile test was the only parameter in which it was observed that the laminate produced by the infusion method had the lowest value compared to the other methods, at 3,600 MPa. In contrast, the value for the vacuum bag was 5,900 MPa, so it was 39 % higher, and for the hydraulic press it was 8,900 MPa, which was 60 % higher. In the case of the tensile strength of the laminate produced by the three described methods, the values were similar, at 540 MPa for infusion, 520 MPa for vacuum bagging and 450 MPa for a hydraulic press.

A test performed on a pendulum hammer to determine the ability of the composites to withstand sudden loads by determining their impact strength determined the impact strength value for plane-loaded infusion composites to be 67.375 kJ/m^2, which was 4 % higher than the impact strength determined in plane loading of the composite made by the press method, and 32 % higher than the laminate made by the vacuum bag method. For the composite samples from the edge-loaded infusion process, the impact strength was 56.898 kJ/m^2 and was thus 16% higher than the impact strength determined with edge-loading of the composite from the hydraulic press and the laminate obtained by the vacuum bag method.

Almost all of the conducted strength tests indicate better mechanical properties of the infusion-produced composite. It was characterised by better flexural strength, tensile strength and impact strength. Only the mean elastic modulus was a parameter in which infusion was inferior to the other methods. The obtained results lead to a conclusion that the infusion method produces the most mechanically strong composite, while laminates made using the hydraulic press and vacuum bag method are created in a shorter time, but are inferior to infusion composites in terms of strength. A factor that determines the inferior mechanical properties of press-and-bag composites is the phenomenon of loss of part of the resin under pressure. The freshly soaked carbon mats drain the resin onto the edges of the PET film under force, so that the composite does not cure with all the resin spread on it during the manufacturing process. In the infusion method, dry carbon mats are soaked in the resin during the curing process, so that the loss of resin is minimised. This is demonstrated by the masses of the samples (a 10 mm wide, 150 mm long 'paddle' shape) made by each method:

- average weight of infusion samples 5.43 g (3.62 kg/m^2);
- average weight of samples from the hydraulic press process 4.68 g (3.12 kg/m^2);

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– average weight of samples from the vacuum bag process 5.16 g (3.44 kg/m^2).

The masses of the samples show that infusion results in the least resin loss during the curing process, allowing composites made by means of this method to achieve the best mechanical properties. In addition, the infusion method also allows the layers of carbon mats to bond well together. The mass of the samples produced by the hydraulic press process shows the greatest resin loss under the applied forces. Despite these losses, the composite had better properties than the composite produced by the vacuum bag method. This is due to better bonding of the carbon mat layers in the hydraulic press method.

5. CONCLUSIONS

Based on the conducted experiments, the following conclusions were drawn:
- laminates produced by the vacuum bag and hydraulic press methods are characterised by the lowest consumption of materials for their production and the shortest preparation time;
- composites produced by the infusion method have the best mechanical properties of the examined manufacturing methods;
- with the selected parameters of the manufacturing technology, the method using a hydraulic press produced the composite with the lowest surface mass;
- the infusion method achieves the least resin loss during the curing process and good bonding of the fibre layers;
- the process of producing the composite in a hydraulic press had the highest resin losses, but allowed better bonding of the carbon fibre layers to be achieved, which determined its better mechanical properties with regard to the vacuum bag method;
- the manufacture of the laminates using the vacuum bag method results in low resin losses. The laminates manufactured with this method have poorer strength characteristics than those produced with the infusion or hydraulic press methods.

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