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MANUFACTURING GEARBOX HOUSING CASE MADE OF CARBON FIBER REINFORCED POLYMER COMPOSITE BY AUTOCLAVE METHOD

The aim of the study was to verify the possibility of reproducing a steel, welded gear body element, using an epoxy-carbon composite, as an adaptation project. The content includes a description of the design and manufacturing process along with an indication of the problems occurring at various stages. The design procedure included product optimization, mold design, and composite structure design. The molded element was to be a composite monolithic structure and was intended for vibroacoustic studies. The wall thickness of the element was to be 6÷10 mm. Pre-impregnated fabric (so-called prepreg) with an areal mass of 240 g/m^2 (outer layers) and 800 g/m^2 (structural layers) was used as the material. The matrix was epoxy resin. The technological procedure included producing the mold and molding the product using the produced mold. The mold was made by milling with a 5-axis milling center (CNC), based on a block assembled of epoxy panels. The molding of the product was started by manually lining the mold with a layup of prepregs. During laying, consolidation was carried out several times using a vacuum bag. A full vacuum packet (vacuum foils, breather, delamination fabric) was applied to the layup. The preformed layup was cured in an autoclave at 120°C, at the pressure of 4 bar and a set –1 bar vacuum inside the packet. The total process time was 4 hours. It was found that the obtained product very accurately reproduces the steel housing and meets the assumptions of the comparative element for vibroacoustic testing. The use of the composite allowed the weight of the element compared to the original to be reduced by over 80% without taking into account the weight of additional steel elements necessary for installation and by over 60% including the weight of those elements. The performed procedures and their effect confirm that polymer matrix composite materials are very well suited for reproducing products and creating prototypes.

Keywords: polymer matrix composite, carbon fiber, autoclave molding, adaptation project

WYTWORZENIE ELEMENTU OBUDOWY PRZEKŁADNI Z KOMPOZYTU POLIMEROWEGO WZMOCNIONEGO WŁÓKNEM WĘGLOWYM METODĄ AUTOKLAWOWĄ

Celem pracy była ocena możliwości odtworzenia stalowego, spawanego elementu korpusu przekładni zębatej z kompozytu epoksydowo-węglowego, na zasadach projektu adaptacyjnego. Opisano proces projektowania oraz wytwarzania wraz ze wskazaniem problemów występujących na różnych etapach. Procedura projektowania obejmowała optymalizację wyrobu, projektowanie formy oraz projektowanie struktury kompozytu. Formowany element miał stanowić kompozytową strukturę monolityczną i był przeznaczony do badań wibroaktywności. Grubość ścianek elementu miała wynosić 6÷10 mm. Jako materiał zastosowano tkaninę preimpregnowaną (tzw. pre-preg) o gramaturze 240 g/m^2 (warstwy zewnętrzne) oraz 800 g/m^2 (warstwy konstrukcyjne). Osnowę stanowiła żywica eposksydowa. Procedura technologiczna obejmowała wykonanie formy oraz formowanie wyrobu z jej użyciem. Formę wykonano metodą frezowania z użyciem 5-osiowego centrum frezerskiego (CNC) na bazie półfabrykatu z płyty epoksydowych. Formowanie wyrobu rozpoczęto od ręcznego wyłożenia formy stosem pre-pregów. Podczas układania kilkukrotnie przeprowadzano konsolidację z użyciem worka próżniowego. Na ułożonym stosie zastosowano pełny pakiet próżniowy (folie uszczelniające, breather, delaminaż). Wstępnie uformowany stos utwardzano w autoklawie, w temperaturze 120°C, przy ciśnieniu o wartości 4 bar i zadanym podciśnieniu wewnątrz pakietu –1 bar. Całkowity czas procesu wyniósł 4 h. Stwierdzono, że uzyskany wyrób stanowi bardzo dokładne odwzorowanie obudowy stalowej oraz spełnia założenia elementu porównawczego do badań. Zastosowanie kompozytu pozwoliło na obniżenie masy odtwarzanego elementu w porównaniu z pierwowzorem: o ponad 80% bez uwzględnienia masy dodatkowych elementów stalowych, koniecznych do domontowania i o ponad 60% z uwzględnieniem masy tychże elementów. Wykonane działania i ich efekt potwierdzają, że polimerowe materiały kompozytowe bardzo dobrze nadają się do odtwarzania wyrobów w wymiarze jednostkowym oraz tworzenia prototypów.

Słowa kluczowe: kompozyt polimerowy, włókno węglowe, formowanie w autoklawie, projekt adaptacyjny

INTRODUCTION

Fiber reinforced plastic (FRP) composites are currently of the most popular groups of construction materials. They are primarily characterized by very good mechanical properties and low weight at the same time

[1, 2]. They are also resistant to corrosion, which in many applications makes them competitive with steel [3].

One of the widespread applications of FRP composites is the production of single products (non-serial production), as well as the reconstruction of specific elements originally made of other materials. The entirety of activities related to planning the reconstruction of an object and its implementation can be called an adaptation project.

FRP composites are great as materials for adaptation projects. The number of advantages of this group of materials includes first of all, the possibility of structure selection and design [4, 5]. This makes it possible to "control" the material properties, which in turn leads to the possibility of far-reaching optimization. Another advantage of FRP composites is their universality in terms of forming possibilities [5, 6]. They can be formed in many ways and in various conditions, including modern automated methods of very high precision [7]. It gives the possibility of wide and non-standard use. FRP composites can be structurally combined with other materials [8, 9]. This further extends their applicability. In addition to structure design capabilities, FRP composite components [10] can be modified physically [11, 12] and chemically as needed. An example here may be modifications with nanoadditives [13, 14]. This is another method that can be used to customize and optimize the FRP composite for a particular application.

In addition to the technological advantages mentioned, FRP composites also have very good typical material properties, which predestines them for various types of constructions. A very important feature of FRP composites is the favorable (non-violent) course of destruction [15, 16]. It guarantees significant security of structures made of this type of materials [17]. In recent years, it has also been found that FRP composites exhibit satisfactory fatigue and thermal properties [18] and do not significantly change their properties under the influence of liquid soaking [19]. These properties are of particular importance, among others in the case of gear housings. Gearboxes are characterized by both an increased temperature, the presence of oil within the housing, as well as vibrations and cyclic loads caused by rotational motion [20]. The only significant limitation of FRP composites is the maximum operating temperature below 120°C - not counting special solutions, which, however, are extremely expensive.

The aim of the study is to assess the possibility of reconstructing a gearbox body element using an epoxy-carbon composite, based on the principles of an adaptation project. The content includes a description of the design and manufacturing process along with an indication of the problems occurring at various stages. In the final part of the work, the technological validity of the adopted method and the manufactured product were assessed.

Carbon fibers adopted as reinforcement of the composite discussed in this paper are used in products of particularly high quality. They are characterized primarily by a high modulus of elasticity, compared to other types of fibers [2, 6]. The main disadvantage of carbon fibers is the relatively high price. The material and manufacturing technology were adopted as one of the options in a wider project aimed at analyzing the impact of using composite gearbox housing elements on its vibroacoustic response. It has already been shown that the use of composites for gear housing reduces their vibroactivity, especially in high frequency ranges, and is associated with a reduction of 60% in weight [21, 22]. Earlier work on the production of fiberglass-based composite gearbox housing elements performed for the same wide project has already been published [23].

DESIGN AND TECHNOLOGICAL PROCEDURE

The basic premise of the applied procedures was to obtain a product as geometrically close as possible to the original. The first stage of the project involved analysis of the basic reinforcing materials and basic models of composite structures used in general technology. Therefore, carbon fiber in the form of a simple cross structure, i.e. fabric, was adopted as the reinforcement. Due to the availability of autoclave technology and in connection with the requirement of high accuracy of implementation, a procedure without the direct use of a real model was adopted. It was based on numerical design of the mold and its implementation on a CNC milling machine (CAD/CAM support).

The design procedure involved three stages: *product optimization, mold design, and composite structure design.*

First, the composite housing design was prepared, making the necessary optimization. This process was necessary due to the different properties of composite materials reinforced with continuous fiber than steel, as well as owing to technological limitations. The steel body being the original model is shown in Figure 1.

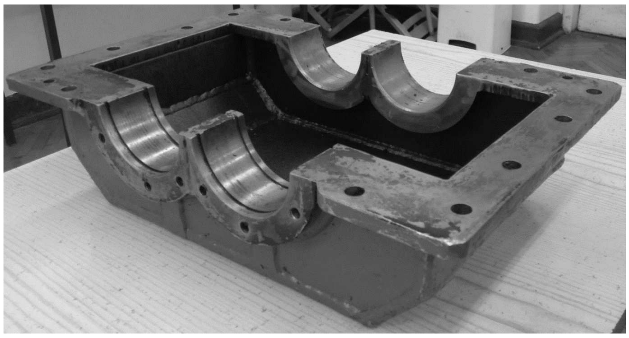

Fig. 1. Upper gearbox housing - original element that was reproduced as part of the project

Rys. 1. Górna obudowa przekładni zębatej - rzeczywisty element, który odtwarzano w ramach projektu

The body was made by welding technology and is characterized by low dimensional accuracy and large welds. It also has an inner flange with a width of

22 mm, in which grooves for bearings are milled (Fig. 2a). Making a composite body with an internal flange is hard and complicated for technological reasons. With negative angles or internal surfaces, it is impossible to remove the finished product from the mold. The solution in this case could be a complex, multi-part mold, but its implementation is expensive, hence this solution was abandoned in the design. What is more, composites reinforced with carbon fiber are characterized by very high stiffness, which is why in this case an additional inner flange is not needed. Therefore, the decision was made to remove the inner flange and stick (by glue) the metal bearing-pans as additional elements in a later operation (Fig. 2b).

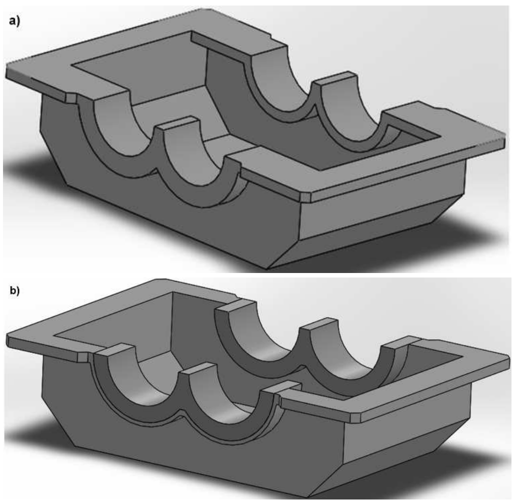

Fig. 2. 3D image of numerical model of product: a) full product model according to original, b) product model without internal parts of stiffening flange together with bearing ring inserts modeled

Rys. 2. Obraz 3D modelu numerycznego wyrobu: a) pełny model wyrobu wg oryginału, b) model wyrobu pozbawiony wewnętrznych części kołnierza usztywniającego wraz z modelami wstawek wieńców łożyskowych

Near the bearing-pans, an external composite flange with a thickness of 4 mm was designed, providing a surface for gluing inserts. A model of 16 mm thick metal inserts was also prepared in which holes and grooves for bearings will be milled. During operation of the transmission, vibrations will be transferred through the bearings and the metal inserts to the composite body. The contact point of the pans of two adjacent bearings is the point of stress concentration, therefore it was rebuilt; the thickness was increased to obtain better local reinforcement and flat surfaces were derived to avoid sharp, angular ends, as shown in Figure 3.

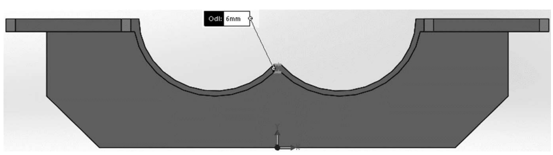

Fig. 3. Diagram of local thickening of flange wall in area particularly exposed to loads during gear operation

Rys. 3. Schemat lokalnego pogrubienia ścianki kołnierza w obszarze szczególnie narażonym na obciążenia podczas pracy przekładni

In the next stage of the work, based on the finished composite product model, the design of the mold was started. For the discussed case, a convex form was adopted, which allows an internal smooth and aesthetic surface to be obtained. The purpose of such a mold construction is to accurately reproduce the geometry of the surfaces to which the bearing-pan inserts will be glued, as well as the possibility of additional reinforcement of this place on the opposite side. When designing the mold, the specificity of composite materials and the selected technological process were taken into account. Edge rounding (Fig. 4b), vertical wall convergence (Fig. 4c) were added, the base of the mold was enlarged and grooves limiting the size of the product were added (Fig. 4d). From the bottom of the mold, a pocket was made for even heating in the curing process (Fig. 5a). The virtual assembly image of the mold and the finished product is shown in Figure 5b.

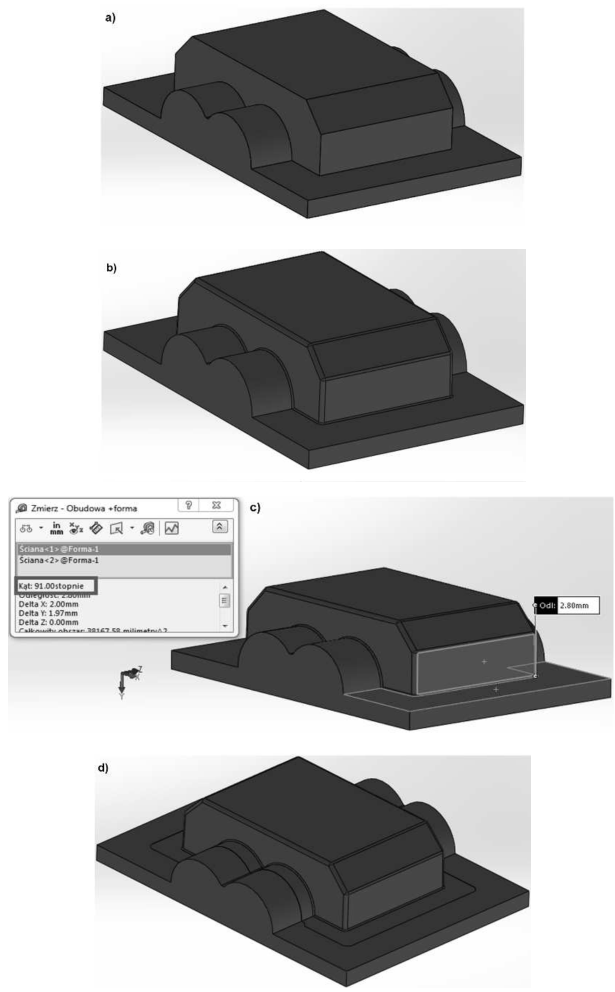

Fig. 4. Important stages of modifying numerical model of designed mold for gear housing: a) initial model being the negative of product model, b) model with rounded edges, c) introducing convergence into model enabling subsequent removal of product from mold, d) view of groove limiting size of product

Rys. 4. Istotne etapy modyfikacji modelu numerycznego projektowanej formy dla obudowy przekładni: a) model wyjściowy będący negatywem modelu wyrobu, b) model z zaokrąglonymi krawędziami, c) wprowadzanie do modelu zbieżności umożliwiających późniejsze odformowanie wyrobu od formy, d) widok wyżłobienia ograniczającego rozmiar wyrobu

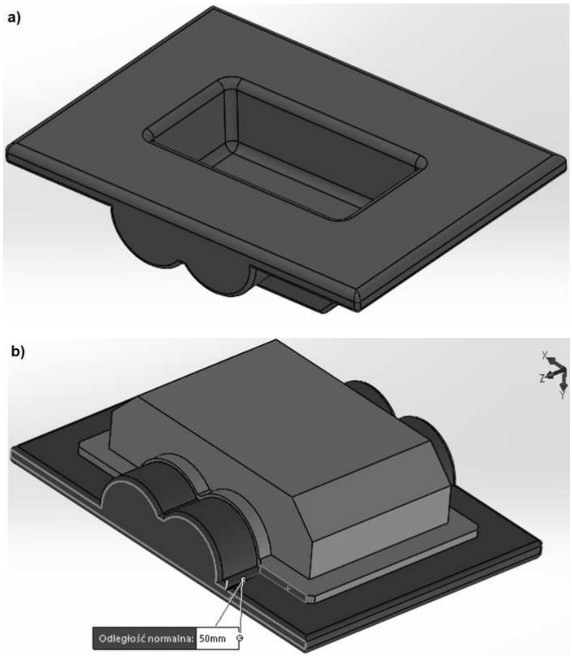

Fig. 5. Complementary images to mold design process: a) optimized internal (non-working) side of mold, b) assembly of product model to mold model

Rys. 5. Obrazy uzupełniające do procesu projektowania formy: a) zoptymalizowana wewnętrzna (nie robocza) strona formy, b) nałożenie modelu wyrobu na model formy

Designing the structure of the composite included selecting the type of prepregs, as well as the number and orientation of layers. For the need of vibroactivity analysis, the body was to be a monolithic FRP composite structure. The body thickness was to be 6 mm and at the outer flange 10 mm. To make the visual layers, i.e. the first and last layer, pre-impregnated fabric (so-called prepreg) with an areal mass of 240 g/m^2, 2x2 twill weave, pre-impregnated with epoxy resin was selected. According to the manufacturer, one layer of laminate is 0.28 mm thick. To implement the structural layers, pre-impregnated fabric with an areal mass of 800 g/m^2, 2x2 twill weave, pre-impregnated with epoxy resin was selected. According to the manufacturer, one layer of laminate is 0.89 mm thick. The matrix of both prepregs was a similar epoxy resin with a high degree of transparency and gloss. The maximum temperature of its use is 135°C. The technical specifications of the resin and fibers are more strictly confidential.

For the main body part with the thickness of 6 mm, the material layout shown in Figure 6a was chosen. The subsequent layers of the fabric were alternately laid at 0/90° and +/–45° fiber orientation to provide quasi-isotropic properties. The same arrangement of layers was also decided on to take on the part of the collar where the metal inserts were glued. The design of the mold allowed for such a modification, and it was dictated by an increase in the structural safety of the housing. The structure of the 10 mm thick outer flange is shown in Figure 6b.

The technological procedure involved two main activities: *manufacturing the mold and forming the product on the manufactured mold*.

The mold was made by milling with a 5-axis CNC Jobs Jomah milling center, based on a previously prepared block assembled of epoxy foam panels Axon LAB 975 (Fig. 7a). After machining, the mold was polished up and then 12 layers of sealant were applied, which clogs the pores and creates a tight, smooth mold surface. Before the lamination process, FREKOTE 700-NC release agent from LOCTITE was applied to the surface. The agent was applied using paper cloths. To obtain a good non-stick coating, 4 layers of release agent were applied (Fig. 7b).

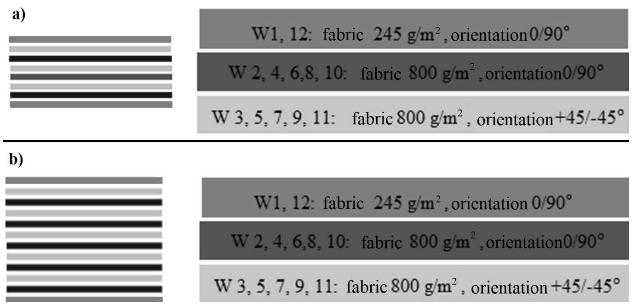

Fig. 6. Diagram of prepreg layer layup creating basic structure of composite: a) used to form side walls of gear housing, b) used to form flange

Rys. 6. Schemat stosu warstw prepregów tworzącego zasadniczą strukturę kompozytu: a) wykorzystanego do formowania bocznych ścian obudowy przekładni, b) wykorzystanego do formowania kołnierza

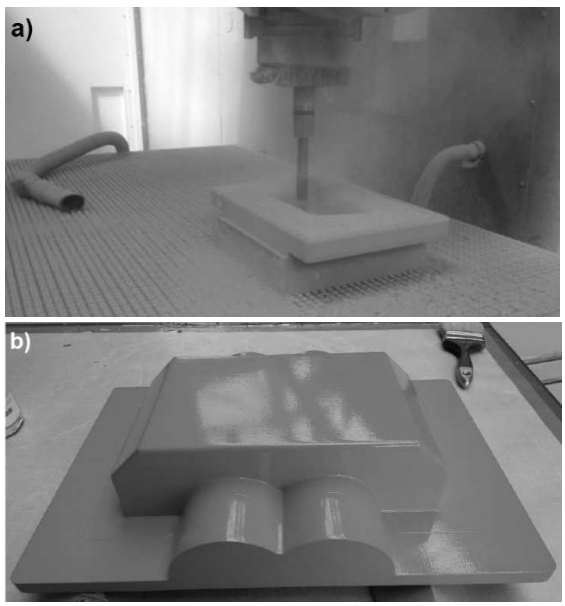

Fig. 7. Production of mold for autoclave process: a) milling mold on CNC device, b) ready mold, covered with release agent

Rys. 7. Wytworzenie formy do procesu autoklawowego: a) frezowanie formy na urządzeniu CNC, b) gotowa forma, pokryta środkiem rozdzielającym

After the mold was prepared, it was used to carry out the manufacturing process of the gearbox. The first stage of the process was manual lining of the mold with prepreg cuts to obtain the desired layup. To receive a product with a high aesthetic value, special attention was paid to the first layer to make it look aesthetic by masking all the connections. Then the consolidation process was carried out in a vacuum bag, i.e. the prepreg was compacted, air was removed from under the fabric and good adhesion to the mold was ensured. Then the vacuum bag was removed and the remaining prepreg layers were put into the mold, using the consolidation process again after the fourth and sixth layers. The mold with all the prepreg layers is shown in Figure 8a.

In the next step, the functional layers included in the vacuum package for the autoclave curing process were laid. Due to the need to obtain an aesthetic surface on the side opposite to the form, the package was planned and made very carefully. Template sheets of rigid, perforated glass fabric coated with Teflon were laid directly on the carbon fabric (Fig. 8b). Further materials included in the vacuum bag are the delamination fabric making it possible to obtain a developed surface; a separating film, whose task is to keep the resin in the system and isolate it from the plastic sleeve; a breather type nonwoven fabric allowing air to flow inside the packet; a high-temperature polyamide foil constituting an external bag; and sealing tape allowing the vacuum bag sheet to be closed and sealed. The ready vacuum packet is shown in Figure 8c. The packet thus prepared goes to the autoclave (Fig. 8d).

The initially molded layup in the vacuum packet was cured at 120°C, at the pressure of 4 bar and vacuum of –1 bar inside the package. The exact course of the autoclave curing process is shown in Figure 9.

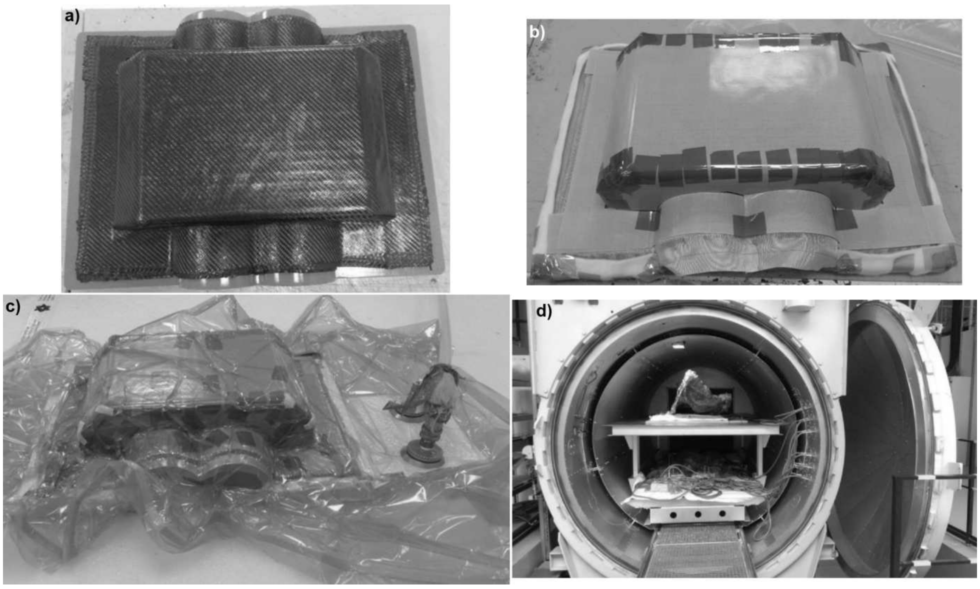

Fig. 8. Product molding process: a) layup of subsequent prepreg layers applied to mold, b) functional layer pack applied to prepreg layup, c) vacuum packet for curing process, d) prepared packet put into autoclave

Rys. 8. Proces formowania wyrobu: a) stos kolejnych warstw prepregów nałożony na formę, b) pakiet warstw funkcyjnych nałożony na stos prepregów, c) pakiet próżniowy do procesu utwardzania, d) przygotowany pakiet wprowadzany do autoklawu

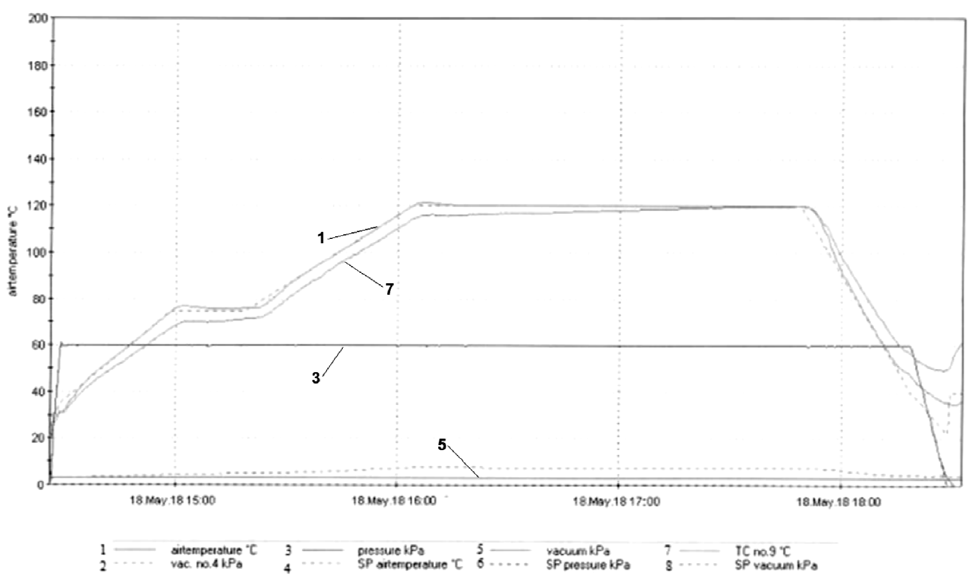

Fig. 9. Course of autoclave process - process parameter values vs. time

Rys. 9. Przebieg procesu autoklawowego - wartości parametrów procesu w czasie

After a successfully finished curing process, the mold was removed from the autoclave, the vacuum bag was removed, and the finished product was removed from the mold with the help of tools. Figure 10 shows the gearbox body before removing it from the mold (a) and after removing it from the mold (b).

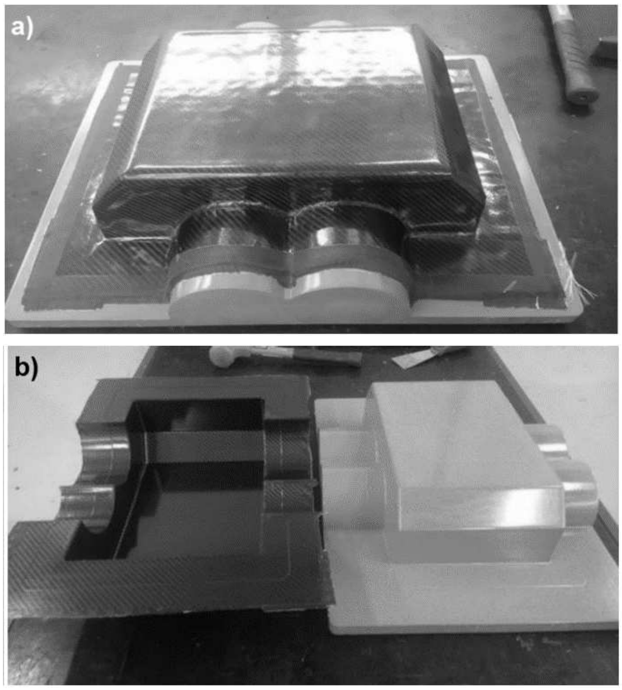

Fig. 10. After autoclave process: a) product on mold, b) product after removing from mold

Rys. 10. Po procesie autoklawowym: a) wyrób na formie, b) wyrób po zdjęciu z formy

PRODUCT EVALUATION

The manufactured product after treatment consisting in removing technological allowances from the edges, is shown in Figure 11.

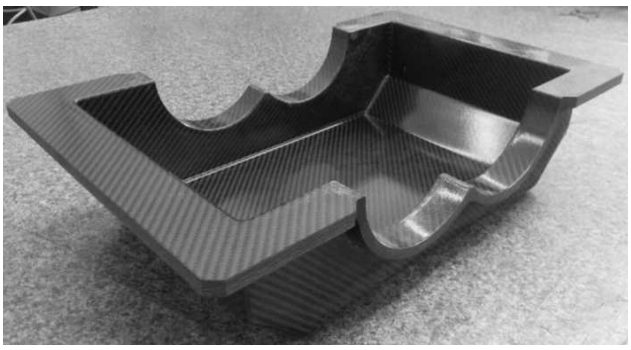

Fig. 11. Finished product after processing side edges from allowances

Rys. 11. Gotowy wyrób po obrobieniu bocznych krawędzi z naddatków

The manufactured element was first subjected to visual assessment. Very good quality and aesthetics of the internal surface of the element and satisfactory quality of the external surface were found. As a result of inaccurate matching of the Teflon coated glass fabric templates under pressure, there are streaks on the vertical surfaces on the longer sides of the element, shown in Figure 12, in which the outer layers of prepreg curled, creating a folded surface. The reason is the high stiffness of both the prepregs themselves and the functional glass fabric coated with Teflon, which makes it impossible to locally adjust the shape around the bends with a small angle of curvature (on the one hand the wall has an external bend, on the other internal). Local disturbances in the direction of the fiber arising in the vicinity of small angles of curvature are "transferred" to the wall plane.

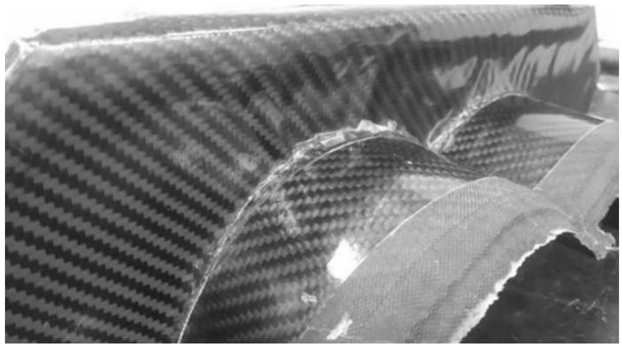

Fig. 12. Inaccuracy of adhesion of outer layers in bend area with small radius of curvature

Rys. 12. Niedokładność przylegania zewnętrznych warstw w obszarze zgięcia o małym promieniu krzywizny

There was also slight porosity at the concave edges around the bearing pan contact areas on the mold side. Despite these (relatively minor) defects, the first produced product of this type has a very high quality.

The mass of the manufactured product was also assessed. The original steel housing weighed 12.99 kg. The produced composite housing has a mass of 1.71 kg. By replacing steel with a composite reinforced with carbon fiber, it was therefore possible to reduce the weight of the product by 86.8%, without taking into account the glued steel bearing shells, which will significantly increase the weight of the element. To account for the impact of the steel shells, their mass was estimated. The volume was determined on the basis of the pan 3D model, then, taking into account the density of carbon steel, the pan mass of 1.59 kg was determined. The element with two steel inserts will weigh 4.89 kg, which will reduce the weight by 62.4% compared to the steel original - this is confirmed by the result obtained in works [21] and [22]. The dimensions of the element were also checked using a caliper and tape measure. All the dimensions are in accordance with the designed model of the case.

It should be mentioned one more time that the solid structure of the composite and geometry accorded to the original case were assumed for the need of vibroacoustic research. Otherwise, optimization of the composite structure concerning the mechanical properties of the materials should result in a much better weight savings effect than that obtained in this study.

CONCLUSIONS

On the basis of the design and technology procedure carried out within the study and observations made during it, the following conclusions can be drawn:

1) The obtained product is a very accurate representation of the original steel casing and meets the assumptions of the reference element for vibroacoustic testing.
2) The resulting product is characterized by relatively thick monolithic walls for a FRP composite element, however, it still has very high quality.
3) The use of the composite allowed a significant reduction in the weight of the reproduced element, compared to the original by over 80% without taking into account the weight of additional steel elements necessary for installation and by over 60% including the weight of those elements.
4) In relation to meeting the design and technological assumptions, the aim of the work has been achieved.
5) In order to fully use the potential of composite materials in the analyzed construction case, the next stage should be to redesign the element in order to further reduce the weight, and thus the manufacturing costs. The above should be achieved alternatively by:
   - using a light core (e.g. made of polymethacrylimide foam) and maintaining the assumed wall thicknesses,
   - reducing the wall thickness and designing appropriate transverse reinforcing walls.
6) The performed procedures and their effect confirm that polymer composite materials are very well suited for reconstructing single products and creating prototypes.

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REFERENCES

[1] Królikowski W., Polimerowe kompozyty konstrukcyjne, WN PWN, Warszawa 2012.

[2] Boczkowska A., Krzesiński G., Kompozyty i techniki ich wytwarzania, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2016.

[3] Chatys R., Kleinhofs M., Panich A., Miskow G., Composite laminates for automotive bumpers and lightweight support structures, Book Series: Engineering Mechanics 24(2018), Eds. C. Fischer, J. Naprstek, 145-148, DOI: 10.21495/91-8-145.

[4] Hyla I., Śleziona J., Kompozyty. Elementy mechaniki i projektowania, Wydawnictwo Politechniki Śląskiej, Gliwice 2004.

[5] Kozioł M., Nasycanie ciśnieniowo-próżniowe zszywanych oraz tkanych trójwymiarowo preform z włókna szklanego, Wydawnictwo Politechniki Śląskiej, Gliwice 2016.

[6] Śleziona J., Podstawy technologii kompozytów, Wydawnictwo Politechniki Śląskiej, Gliwice 1998.

[7] Sorrentino L., Anamateros E., Bellini C., Carrino L., Corcione G., Leone A., Paris G., Robotic filament winding: An innovative technology to manufacture complex shape structural parts, Composite Structures 2019, 220, 699-707, DOI: 10.1016/j.compstruct.2019.04.055.

[8] Lesiuk G., Katkowski M., Correia J., de Jesus A.M.P., Blazejewski W., Fatigue crack growth rate in CFRP reinforced constructional old steel, International Journal of Structural Integrity 2018, 9(3), 381-395, DOI: 10.1108/IJSI-08-2017-0050.

[9] Bellini C., Sorrentino L., Characterization of isogrid structure in GFRP, Frattura Ed Integrita Strutturale 2018, 46, 319-331, DOI: 10.3221/IGF-ESIS.46.29.

[10] Kozioł M., Bogdan-Wlodek A., Myalski J., Wieczorek J., Influence of wet chemistry treatment on the mechanical performance of natural fibres, Polish Journal of Chemical Technology 2011, 13, 4, 21-27.

[11] Olesik P., Kozioł M., Toroń B., Szperlich P., Preliminary evaluation of producing polymer cladding on glass fiber designated for fiber lasers, Composites Theory and Practice (Kompozyty) 2018, 18(3), 140-144.

[12] Meier R., Kahraman I., Seyhan A.T., Zaremba S., Drechsler K., Evaluating vibration assisted vacuum infusion processing of hexagonal boron nitride sheet modified carbon fabric/epoxy composites in terms of interlaminar shear strength and void content, Composites Science and Technology 2016, 128, 94-103, DOI: 10.1016/j.compscitech.2016.03.022

[13] Jesione M., Nowak M., Szperlich P., Kepinska M., Mistewicz K., Toron B., Stroz D., Szala J., Rzychon T., Properties of sonochemically prepared CuInxGa1-xS2 and CuInxGa1-xSe2, Acta Physica Polonica A 2014, 126, 5, 1107--1109, DOI: 10.12693/APhysPolA.126.1107.

[14] Dydek K., Latko-Duralek P., Boczkowska A., Salacinski M., Kozera R., Carbon fiber reinforced polymers modified with thermoplastic nonwovens containing multi-walled carbon nanotubes, Composites Science and Technology 2019, 173, 110-117, DOI: 10.1016/j.compscitech.2019.02.007.

[15] Figlus T., Kozioł M., Diagnosis of early-stage damage to polymer - glass fibre composites using non-contact measurement of vibration signals, Journal of Mechanical Science and Technology 2016, 30, 8, 3567-3576, DOI: 10.1007/s12206-016-0717-1.

[16] Koziol M., Figlus T., Evaluation of the failure progress in the static bending of GFRP laminates reinforced with a classic plain-woven fabric and a 3D fabric, by means of the vibrations analysis, Polymer Composites 2017, 38, 6, 1070-1085.

[17] Kozioł M., Evaluation of classic and 3D glass fiber reinforced polymer laminates through circular support drop weight tests, Composites Part B, 2019, 168, 561-571, DOI: 10.1016/j.compositesb.2019.03.078.

[18] Jakubczak P., Bienias J., Surowska B., Interlaminar shear strength of fibre metal laminates after thermal cycles, Composite Structures 2018, 206, 876-887, DOI: 10.1016/j.compstruct.2018.09.001.

[19] Dadej K., Bienias J., Surowska B., On the effect of glass and carbon fiber hybridization in fiber metal laminates: Analytical, numerical and experimental investigation, Composite Structures 2019, 220, 250-260, DOI: 10.1016/j.compstruct.2019.03.051.

[20] Skoć A., Świtoński E., Przekładnie zębate. Zasady działania. Obliczenia geometryczne i wytrzymałościowe, WN PWN, Warszawa 2016.

[21] Figlus T., Kozioł M., Kuczyński Ł., Impact of application of selected composite materials on the weight and vibroactivity of the upper gearbox housing, Materials 2019, 12, 2517, DOI: 10.3390/ma12162517.

[22] Figlus T., Kozioł M., Kuczyński Ł., The effect of selected operational factors on the vibroactivity of upper gearbox housings made of composite materials, Sensors 2019, 19, 4240, DOI: 10.3390/s19194240.

[23] Smoleń J., Cyganek A., Kozioł M., Manufacture of transmission housing by contact layer technique using vacuum bag, Composites Theory and Practice 2019, 19, 1, 18-22.

