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COMPOSITES THEORY AND PRACTICE

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SURFACE QUALITY AND MECHANICAL PROPERTIES OF EPOXY-GLASS FIBRE LAMINATES MANUFACTURED BY VARI METHOD WITH USE OF GELCOAT

The aim of the study is a preliminary evaluation of the possibility and purposefulness of applying a gelcoat covering on GFRP (glass fibre reinforced polymer) laminates manufactured by the VARI (vacuum assisted resin infusion) method. A set of panels was manufactured on the basis of three types of glass fibre reinforcements: plain-woven fabric, chopped strand mat and 3D non-crimp fabric, while the composite matrix was epoxy resin. Alternatively, panels with and without the gelcoat layer were manufactured. The polyester gelcoat was laid on the mould by hand. Profilographometric tests were applied as the main method of evaluating the laminate surfaces. To evaluate the border area between the gelcoat layer and the laminate, microscopic visualization was performed with use of a scanning electron microscope (SEM) and - for chosen specimens - with use of a light microscope in Nomarski's contrast conditions. In order to evaluate the influence of the gelcot layer presence on the laminate mechanical properties, tests of static bending were conducted on the laminates with and without the layer. The obtained profilographometric results showed that application of the gelcoat resulted in improvement of surface quality (a decrease in the maximum and average profile height as well) practically in all the tested specimens. Micrographs made of the gelcoat-laminate border area confirm very good coupling between these two elements. The obtained results of the bending tests showed that the presence of the gelcoat layer does not significantly affect the mechanical performance of the laminates. The registered differences in flexural strength between the specimens with the gelcoat covering and those without it are not big - and in most cases they are in favor of the latter ones. The obtained results allow the authors to conclude that VARI technology is very well suited to manufacturing products with a gelcoat layer. The results and conclusions obtained within the study may be useful for manufacturers in planning and optimization of manufacturing processes for elements made of composite laminates.

Keywords: laminate, gelcoat, vacuum assisted resin infusion (VARI)

POWIERZCHNIA ORAZ WŁAŚCIWOŚCI MECHANICZNE LAMINATÓW ŻYWICA EPOKSYDOWA - - WŁÓKNO SZKLANE WYTWORZONYCH METODĄ INFUZJI PRÓŻNIOWEJ Z ZASTOSOWANIEM ŻELKOTU

Celem niniejszej pracy jest wstępna ocena możliwości i celowości stosowania powłoki żelkotowej na laminaty wytwarzane metodą VARI (ang. *vacuum assisted resin infusion*, pol. *infuzja próżniowa*). Wytworzono zestaw płyt z laminatów na bazie trzech typów wzmocnień włókna szklanego: tkaniny krzyżowej, maty, tkaniny 3D. Płyty z laminatów formowano metodą VARI z użyciem żywicy epoksydowej. Wytworzono alternatywnie płyty bez oraz z warstwą żelkotu. Żelkot nakładano pędzlem. Jako główny element oceny powierzchni wytworzonych laminatów zastosowano badania profilografometryczne. Do oceny obszaru połączenia żelkotu z laminatem zastosowano wizualizację mikroskopową przeprowadzoną z użyciem mikroskopu skaningowego oraz (dla wybranych próbek) z wykorzystaniem mikroskopu świetlnego w kontraście Nomarskiego. W celu oszacowania wpływu obecności żelkotu na właściwości mechaniczne laminatu przeprowadzono próby zginania statycznego laminatów zi bez warstwy żelkotu. Uzyskane wyniki profilografometryczne pozwalają stwierdzić, że zastosowanie żelkotu praktycznie we wszystkich przypadkach spowodowało polepszenie jakości powierzchni laminatu, tzn. spadek zarówno maksymalnej, jak i średniej wysokości profilu tejże powierzchni. Zdjęcia mikroskopowe wykonane na granicy żelkot-laminat świadczą o bardzo dobrym połączeniu między tymi dwoma obszarami. Uzyskane wyniki prób zginania pozwalają stwierdzić, że wpływ żelkotu nie jest istotny dla właściwości mechanicznych laminatów. Zarejestrowane różnice wytrzymałości są niewielkie, przy czym z reguły na korzyść próbek z żelkotem. Na podstawie uzyskanych wyników można stwierdzić, że technologia VARI bardzo dobrze nadaje się do wykonywania wyrobów z warstwą żelkotu. Wyniki te mogą być pomocne przy planowaniu oraz optymalizacji struktur i technologii stosowanych na elementy konstrukcyjne z kompozytów.

Słowa kluczowe: laminat, żelkot, infuzja próżniowa

INTRODUCTION

The aim of this study is a preliminary evaluation of the possibility and purposefulness of applying a gelcoat cover layer on GFRP (glass fibre reinforced polymer) laminates manufactured by the VARI (vacuum assisted resin infusion) method [1, 2]. The method is currently very intensively implemented since it enables the production of laminates exposing workers to lower levels of solvent vapours and it results in better repeatability in comparison with hand lay-up manufacturing [3, 4]. Due to the specific conditions of the VARI process (vacuum bag pressure for reinforcing layers, resin flow), manufacturers do not apply gelcoat coverings with this technology. They rather prefer painting products with proper paint after the process is finished [5, 6]. The problem of applying gelcoat in pressure- and vacuum-assisted techniques of laminate moulding has practically not been addressed in professional literature. Some mentions are have been made in branch publications, however, they are very general and not precise [7]. Nevertheless, in many types of composites - among others in those reinforced with natural components [8, 9], which are increasingly being applied and investigated [10, 11] - the surface often does not meet the quality requirements. In such situations, the application of gelcoat could be useful, as well as in the case of composites reinforced with non-crimp or stitched fibrous preforms - which was shown by the authors of research preceding this study. An additional advantage of the presence of the gelcoat layer on a laminate is the shielding effect against UV rays.

The undertaken research task consisted in defining the simultaneous effect of the presence of the gelcoat layer and the structure of the reinforcing preform on surface quality and the mechanical properties of laminates manufactured by the VARI method. The problem proposed to analyse arises from the fact that the structure of the laminate is usually subordinated mainly to the requirements related to its strength [4, 12], without the issue of the impact of the structure on the laminate surface quality and technological properties of the fiber preform. Nonetheless, the lack of proper quality of the laminate surface (smoothness, lack of gaps and gas bubbles) may have a negative influence on the mechanical properties of the laminate - especially by the trends of damage arising due to local stress concentrations, even at a relatively low strain of the material [4, 13]. It is a preliminary study on the model structures and model technological conditions. The results may be helpful in the planning and optimization of structures and technologies used for structural components made of composite laminates.

MATERIALS AND TECHNOLOGICAL PROCEDURE

A set of laminate panels was manufactured on the basis of three types of reinforcing glass fibre structures:

1. Plainwoven fabric (10 layers, areal mass 320 g/m^2, KROSGLASS, Poland)
2. Chopped strand mat (6 layers, areal mass 540 g/m^2, KROSGLASS, Poland)
3. 3D fabric (7 non-crimp layers, areal mass 3280 g/m^2, 3TEX, USA).

Panels 320 x 250 mm were moulded by the VARI method, without a bleeder (spreading fabric) - only with vacuum bag foil and release fabric. A diagram of the process is given in Figure 1.

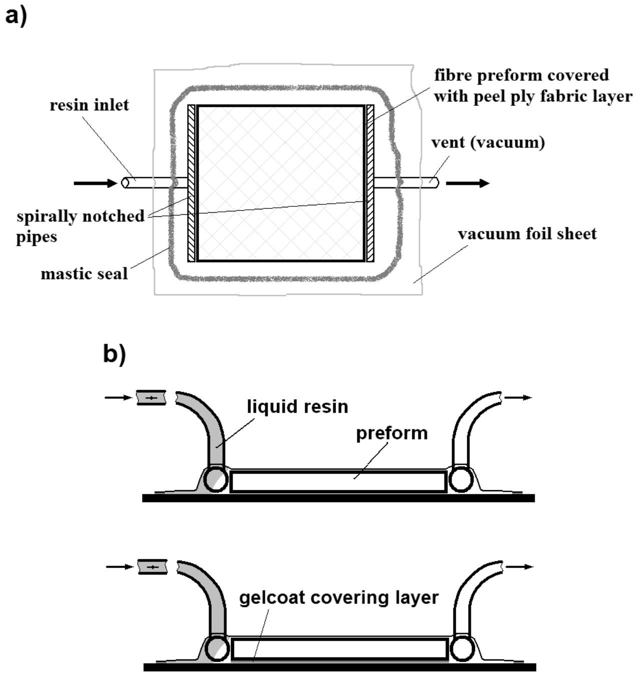

Fig. 1. Diagram of applied VARI system: a) plan view, b) side cross-sectional view and indication of gelcoat covering layer in mould (alternative case)

Rys. 1. Schemat zastosowanego układu VARI: a) widok z góry, b) widok przekroju bocznego ze wskazaniem warstwy żelkotu na formie (dla części próbek)

The power of the vacuum pump was 1100 W. LH 288 epoxy resin with H 281 hardener (both HAVEL COMPOSITES, Czech Republic) was applied as the composite matrix.

The panels were manufactured alternatively with and without the gelcoat layer. The gelcoat was laid on the lower surface of the mould nest with a brush, until it fully covered the entire surface without lumens. Lay-up of the dry reinforcing layers and start of the moulding process were performed after the gelcoat was subjected to initial curing (consistence of rubber). HAVELGEL 2432 gelcoat by HAVEL COMPOSITES, Czech Republic, was applied. After the process, all the panels were cured at room temperature for 20 h and after-cured at 55°C for 4 h. Next they were acclimatized for at least 72 h at room temperature again. Specimens for the tests were prepared with use of a rotating blade.

ANALYTICAL METHODS

Profilographometric investigations were the main method of evaluating the manufactured laminate surfaces. They were performed using a MICRO PROF optical profilographometer by FRT, Germany. The information set concerning the tested materials is shown in Table 1.

TABLE 1. **Description of shorted names of tested specimens applied in further part of study**
TABELA 1. **Objaśnienie nazw badanych próbek zastosowanych w dalszej części pracy**

Shorted name of specimen type	Description
Plain	Laminate manufactured by VARI method on basis of plain-woven fabric
Plain gelcoat	Laminate manufactured by VARI method on basis of plain-woven fabric, with gelcoat layer
Mat	Laminate manufactured by VARI method on basis of chopped strand mat
Mat gelcoat	Laminate manufactured by VARI method on basis of chopped strand mat, with gelcoat layer
3D	Laminate manufactured by VARI method on basis of 3D fabric
3D gelcoat	Laminate manufactured by VARI method on basis of 3D fabric, with gelcoat layer

To evaluate the coupling between the gelcoat layer and the main laminate structure, microscopic visualization of the border area was applied. Pictures of the representative specimens were made with use of a HITACHI S-3400N scanning electron microscope (SEM), equipped with a camera. Additional photographs, showing better contrast, were made using a NIKON ECLIPSE 200 MA light microscope in Nomarski's contrast, equipped with a camera.

In order to evaluate the effect of the gelcoat layer presence on the mechanical properties of the laminate, static bending tests were performed. They were conducted with use of an INSTRON 4469 tester, at a 5 mm/min loading bar velocity and 5 kN loading head. The conditions of the tests were compatible with the PN-EN ISO 14125 standard. The tests were conducted on 5 specimens of each laminate type.

RESULTS AND DISCUSSION

The chosen profilographometric analysis results, enabling comparison of the tested laminates, are presented in Figures 2-7. Below the figures, in Table 2, the main surface parameters of the measured profiles are presented. These parameters were automatically determined by the profilographometer in relation to the proper reference plane, according to the ISO 25178 standard. The measured profile parameters for all the tested samples listed together allow comparison of them and evaluation of the effect of the presence of the gelcoat layer on these parameters.

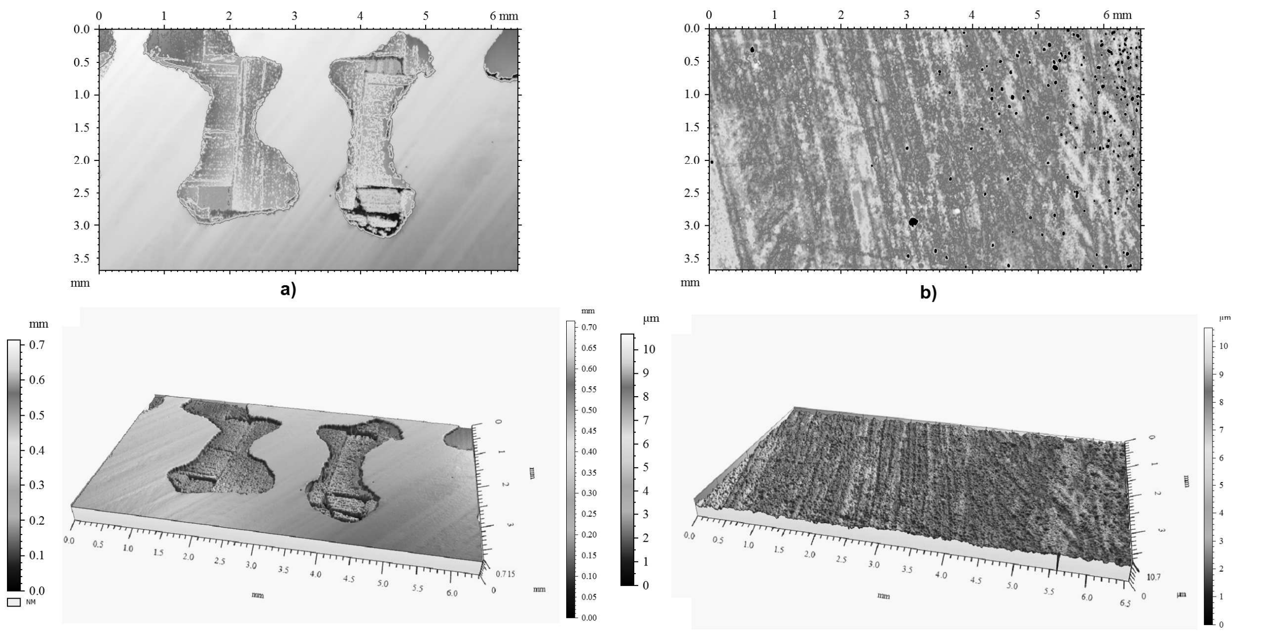

Fig. 2. Isometric image of surface in 2D view (upper) and 3D surface image (lower): a) plain laminate, b) plain gelcoat laminate

Rys. 2. Izometryczny obraz powierzchni 2D (góra) oraz 3D (dół): a) laminat klasyczny, b) laminat klasyczny - żelkot

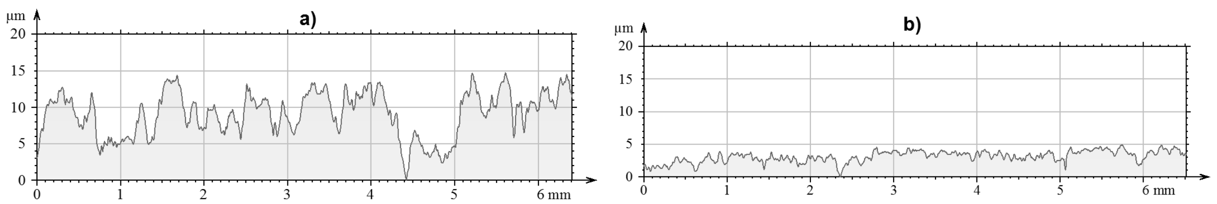

Fig. 3. Distribution of roughness on selected surface area: a) plain laminate, b) plain gelcoat laminate

Rys. 3. Rozkład chropowatości na wybranym fragmencie powierzchni: a) laminat klasyczny, b) laminat klasyczny - żelkot

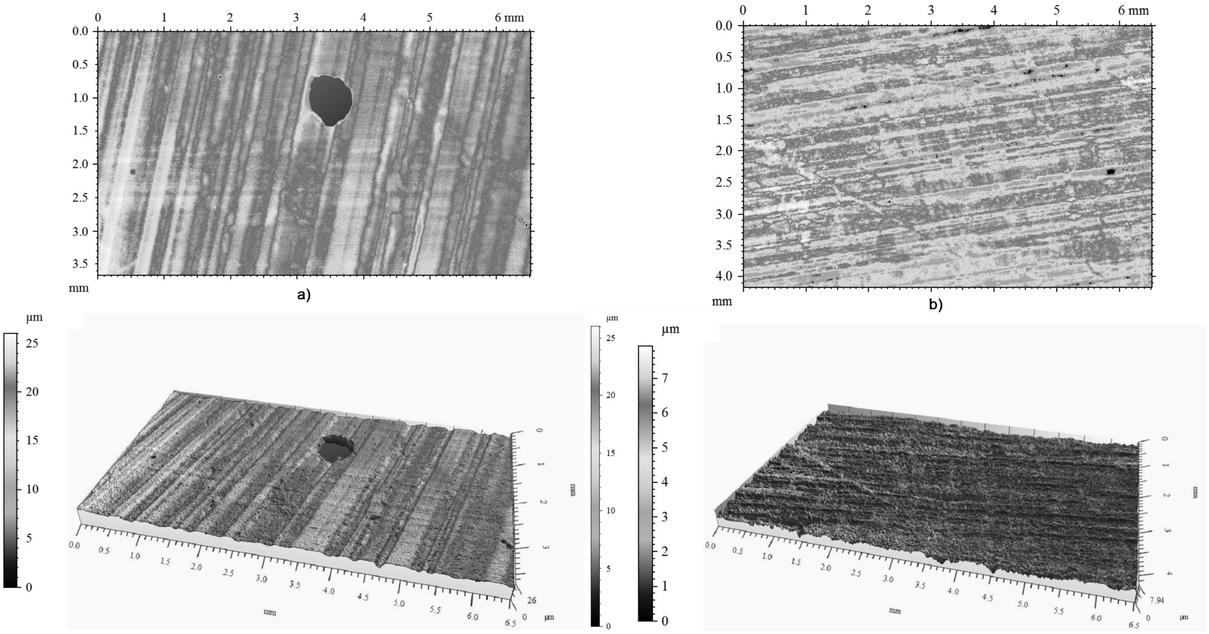

Fig. 4. Isometric image of surface in 2D view (upper) and 3D surface image (lower): a) mat laminate, b) mat gelcoat laminate

Rys. 4. Izometryczny obraz powierzchni 2D (góra) oraz 3D (dół): a) laminat mata, b) laminat mata - żelkot

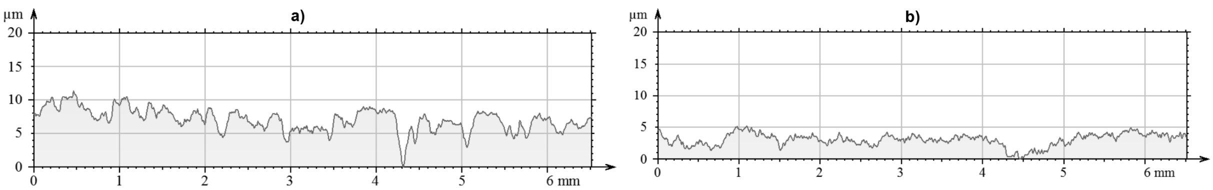

Fig. 5. Distribution of roughness on selected surface area: a) mat laminate, b) mat gelcoat laminate

Rys. 5. Rozkład chropowatości na wybranym fragmencie powierzchni: a) laminat mata, b) laminat mata - żelkot

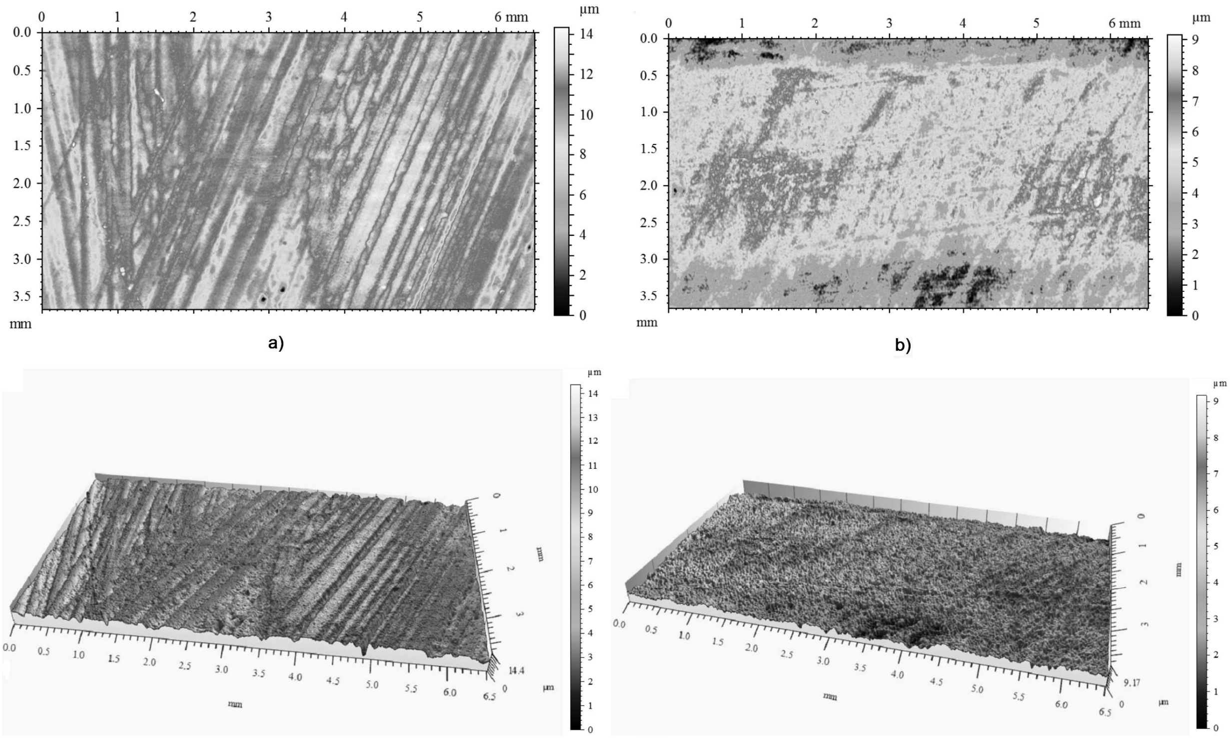

Fig. 6. Isometric image of surface in 2D view (upper) and 3D surface image (lower): a) 3D laminate, b) 3D gelcoat laminate

Rys. 6. Izometryczny obraz powierzchni 2D (góra) oraz 3D (dół): a) laminat 3D, b) laminat 3D - żelkot

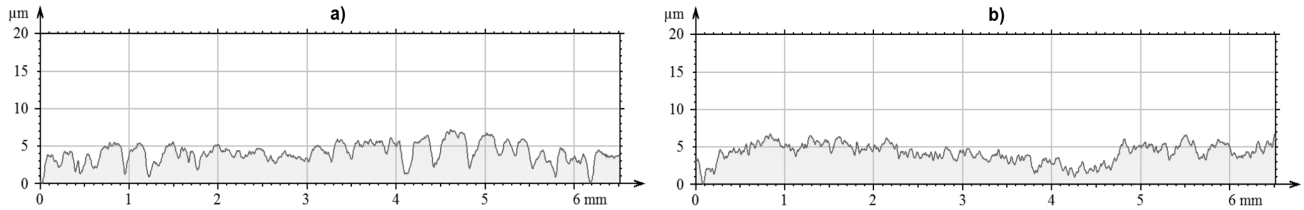

Fig. 7. Distribution of roughness on selected surface area: a) 3D laminate, b) 3D gelcoat laminate

Rys. 7. Rozkład chropowatości na wybranym fragmencie powierzchni: a) laminat 3D, b) laminat 3D - żelkot

TABLE 2. **Chosen surface profile parameters for representative laminate specimens**

TABELA 2. **Wybrane parametry profilu powierzchni dla reprezentatywnych próbek badanych laminatów**

Laminate type	**Maximum height of peaks S_p [μm]***	**Maximum height of valleys S_v [μm]***	**Maximum height of the surface S_z [μm]***	**Arithmetical mean height of the surface S_a [μm]***
Plain	0.138	0.577	715	85.7
Plain gelcoat	2.63	8.04	10.7	0.783
Mat	5.7	20.3	26	1.72
Mat gelcoat	2.78	5.16	7.94	0.901
3D	3.89	10.5	14.4	1.13
3D gelcoat	4.29	4.88	9.17	1.21

* Parameters S_p, S_v, S_z, and S_a were determined automatically by profilographometer in relation to proper reference plane, according to ISO 25178 standard

The obtained results allow one to conclude that the use of gelcoat, in practically all the cases resulted in improving the quality of the laminate surface - it caused a decrease in both the maximum and average height of that surface profile. In the case of the laminates without the gelcoat covering, the tendency to form an outer resin film reproducing the smooth surface of the mould is also visible. However, it is not comparably effective to the case of the gelcoat covering - see the gaps in Figures 2a and 4a. It is probably due to the lower viscosity of neat liquid resin in comparison with the liquid gelcoat mass which is more resistant to shrinkage and leveling.

To evaluate the connection between the gelcoat layer and the main laminate structure, microscopic visualization was used. SEM photographs of the border area taken of representative specimens are presented in Figures 8-10.

The additional photographs of the gelcoat layer - the main laminate structure border, taken of chosen specimens with use of the light microscope (Nomarski's contrast) are presented in Figure 11.

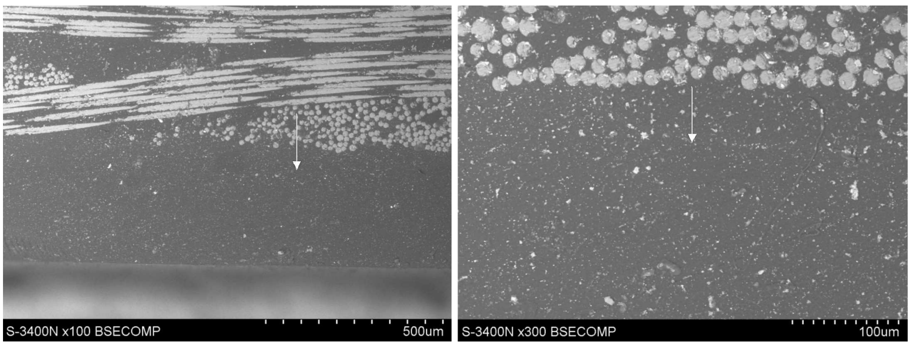

Fig. 8. Gelcoat layer - main laminate structure border (indicated with white arrow) at two different magnifications - plain gelcoat laminate

Rys. 8. Granica warstwa żelkotu - zasadnicza struktura laminatu (zaznaczona białą strzałką) przy dwóch różnych powiększeniach - laminat klasyczny - żelkot

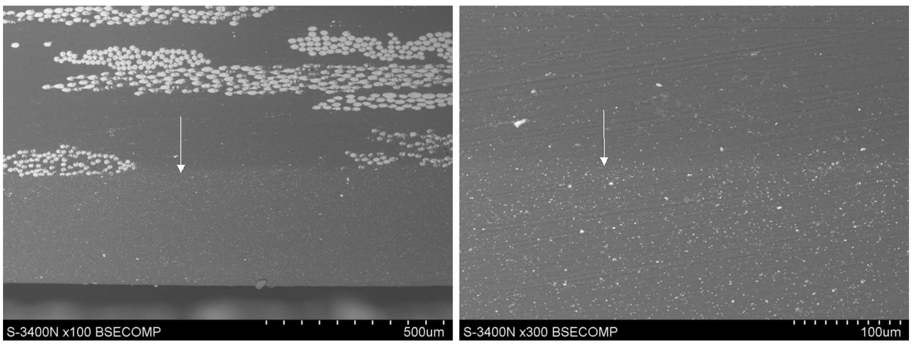

Fig. 9. Gelcoat layer - main laminate structure border (indicated with white arrow) at two different magnifications - mat gelcoat laminate

Rys. 9. Granica warstwa żelkotu - zasadnicza struktura laminatu (zaznaczona białą strzałką) przy dwóch różnych powiększeniach - laminat mata - żelkot

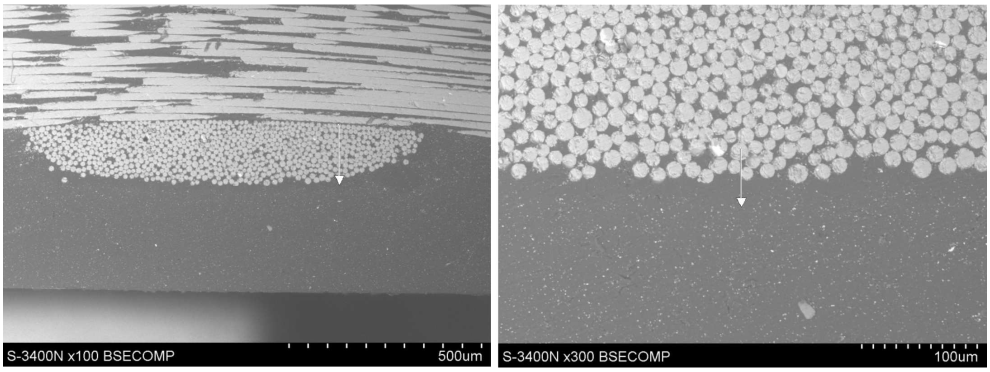

Fig. 10. Gelcoat layer - main laminate structure border (indicated with white arrow) at two different magnifications - 3D gelcoat laminate

Rys. 10. Granica warstwa żelkotu - zasadnicza struktura laminatu (zaznaczona białą strzałką) przy dwóch różnych powiększeniach - laminat 3D - żelkot

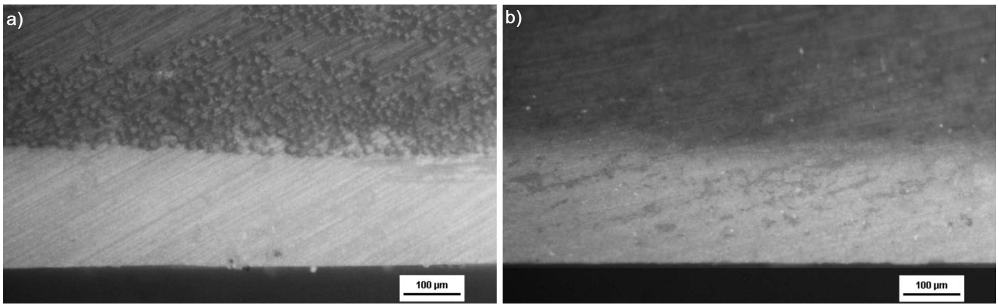

Fig. 11. Gelcoat layer - main laminate structure border - light microscope. Well visible border area: a) plain gelcoat laminate, b) 3D gelcoat laminate.

Rys. 11. Granica warstwa żelkotu - zasadnicza struktura laminatu - mikroskop świetlny. Dobrze widoczny obszar granicy: a) laminat klasyczny - żelkot, b) laminat 3D - żelkot

Practically all the taken photographs testify to the very good connection between the main structure of the laminate and the gelcoat layer. The transition appears to be rather discrete, but with a clear diffusion interlayer in the matrix-gelcoat bonding areas (Fig. 11b) and gelcoat penetration to the fiber strands in the areas of fiber-gelcoat bonding (Fig. 11a). Evaluation of the mechanical properties of the produced laminates in static bending tests was to assess the effect of the application of gelcoat on these properties. Due to the preliminary nature of the study, the mechanical analysis was limited just to static bending tests. The results are shown in Table 3.

TABLE 3. **Results of static bending tests of laminates**

TABELA 3. **Wyniki prób statycznego zginania badanych laminatów**

Laminate type	**Flexural strength R_g [MPa]**	**Deflection at maximum load f_{Rg} [%]**
plain	327 ± 35	2.8 ± 0.7
plain gelcoat	400 ± 18	3.2 ± 0.2
mat	206 ± 5	3.0 ± 1.0
mat gelcoat	287 ±19	4.1 ± 0.2
3D*	534 ± 23	3.8 ± 0.2
3D gelcoat*	488 ± 51	3.5 ± 0.2
* - measured at direction parallel to strands of translaminar interweave		

The obtained results allow one to conclude that the effect of gelcoat presence is not significant for the mechanical performance of the laminates. The registered differences in strength between the laminates with and without the gelcoat covering are slight, especially with regard to the obtained deviations. The differences probably arose from technological causes, other than the presence of the gelcoat (pressure-assisted moulding processes often show a very stochastic course) [13, 4] and from imperfections in arrangement of the laminate layers. By analysing the mechanical results (Table 3) and the profilographometric results (Table 2) together, one may conclude that when comparing the similar types of composites having and not having the gelcoat covering, the influence of the presence of the gelcoat on the mechanical properties of the laminate is obvious: a smoother surface (lower profile heights) and higher flexural strength. Such a trend is visible for the *plain* and *mat* laminates; only the *3D* laminate showed a different trend. It is probably associated with fact that, on the one hand, the gelcoat layer gives smoothness to the laminate surface, but on the other hand, it is susceptible to fracture. A crack arising within the gelcoat layer may relatively easily migrate into the main structure of the laminate, which considerably weakens the material [14, 15]. The obtained results also showed that the deformability of the tested laminates (Table 3) does not change due to the presence of gelcoat covering. In addition, tests of pulling the gelcoat layers out of the laminate main structure were undertaken. Nevertheless, the tests did not succeed due to the strong coupling between these two elements (in fact it is very advantageous for the coupling). Direct evaluation of the strength of this coupling requires preparation of special specimens and a special, non-standard measuring method.

SUMMARY

The fundamental conclusion from the performed analysis is that the application of gelcoat does not negatively affect the mechanical properties of laminates manufactured by the VARI method.

The conducted preliminary tests and analysis showed that VARI technology is suitable for manufacturing products with a layer of gelcoat. It may be applied in conditions similar to the hand lay-up manufacturing method. The obtained surfaces are of high quality - better that those of the equivalent laminates without the gelcoat layers.

The guidelines for possible continuation of research are: further mechanical tests - pulling the gelcoat layers out of the laminate main structure, tests of curved panels, impact tests and at a later stage - manufacturing exemplary comparative products (with and without a gelcoat covering).

Acknowledgements

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