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

The aim of the study was to determine the effect of applying a gelcoat covering on the surface quality and mechanical properties of selected types of glass fibre reinforced polymer (GFRP) laminates produced by the resin transfer moulding (RTM) method. To carry out the investigations, a set of laminate panels was manufactured on the basis of three types of glass fibre reinforcements: plain-woven fabric, chopped strand mat and 3D fabric. They were manufactured by vacuum assisted resin transfer moulding (RTM), alternatively without and with an additional layer of gelcoat. The polyester gelcoat was applied with a brush. As the matrix of the composites, an epoxy resin was used. Evaluation of the manufactured laminate surfaces was conducted using an optical profilographometer, whilst evaluation of the border area between the gelcoat layer and the main structure of the laminate was carried out by microscopic visualization. In order to evaluate the effect of the gelcoat layer presence on the mechanical performance of the laminates, static bending tests were performed. The obtained results allow one to conclude that application of the gelcoat covering resulted in improvement of the investigated laminate surface quality. Decreases in the maximum and average heights of the surface profiles were observed. An especially big difference in the profile height is visible between the 3D laminate without and with the gelcoat covering. Almost all the taken photographs testify to very good coupling between the gelcoat layer and the main laminate structure. The transition between these two elements has a rather discrete character. However, an evident diffusion area occurs in the matrix-gelcoat coupling line and evident penetration of the gelcoat into the fibre strands occurs in the fibre-gelcoat coupling line. It was found that the presence of the gelcoat layer does not have a significant negative effect on the mechanical properties of the laminates. All the tested series of laminates with the gelcoat covering showed a significantly lower standard deviation than the equivalent series of laminates without gelcoat. It means better repeatability of the mechanical properties in the case of the laminates with the gelcoat covering in comparison with those without gelcoat. A consequence of the obtained results is the conclusion that RTM technology is very well suited for manufacturing laminate products with a gelcoat covering.

Keywords: laminate, gelcoat, resin transfer moulding (RTM)

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

Celem pracy było określenie wpływu zastosowania żelkotu na jakość powierzchni oraz właściwości mechaniczne wybranych typów laminatów wytworzonych metodą resin transfer moulding (RTM). Do realizacji celu badań wytworzono zestaw płyt z laminatów na bazie trzech typów wzmocnień szklanych: płóciennej tkaniny rowingowej, maty oraz tkaniny 3D. Uformowano je metodą resin transfer moulding (RTM) w układzie próżniowym. Płyty wytworzono alternatywnie bez użycia oraz z użyciem żelkotu. Żelkot poliestrowy nakładano pędzlem. Jako osnowę laminatów zastosowano żywicę epoksydową. Oceny powierzchni wytworzonych laminatów prowadzono przy użyciu profilografometru optycznego, a ocenę połączenia między warstwą żelkotu a właściwym laminatem prowadzono poprzez wizualizację mikroskopową. W celu oceny wpływu warstwy żelkotu na właściwości mechaniczne laminatu przeprowadzono próby zginania statycznego. Uzyskane wyniki pozwalają stwierdzić, że zastosowanie żelkotu praktycznie we wszystkich przypadkach spowodowało polepszenie jakości powierzchni laminatu, tzn. spadek zarówno maksymalnej, jak i średniej wysokości profilu tej powierzchni. Szczególnie dużą różnicę widać na przykładzie laminatu 3D. Praktycznie wszystkie wykonane fotografie świadczą o bardzo dobrym połączeniu między właściwą strukturą laminatu a warstwą żelkotu. Przejście ma charakter raczej skokowy, jednakże z wyraźną międzywarstwą dyfuzyjną w obszarach łączenia osnowa-żelkot oraz z wnikaniami żelkotu w pasma włókien w obszarach łączenia włókna-żelkot. Stwierdzono, że obecność warstwy żelkotu nie ma istotnego negatywnego wpływu na właściwości mechaniczne laminatów. Wszystkie badane serie próbek z żelkotem wykazały znacznie mniejsze odchylenie standardowe niż serie próbek bez żelkotu, co oznacza lepszą powtarzalność właściwości mechanicznych laminatów z żelkotem w porównaniu z laminatami bez żelkotu. Konsekwencją uzyskanych wyników jest wniosek, że technologia RTM bardzo dobrze nadaje się do wykonywania wyrobów z warstwą żelkotu.

Słowa kluczowe: laminat, żelkot, nasycanie ciśnieniowo-próżniowe (RTM)

INTRODUCTION

Fibre reinforced polymer (FRP) laminates are highly appreciated engineering materials [1, 2]. Currently, one of the main groups of manufacturing technologies for these laminates are pressure- and vacuum-assisted techniques [3, 4], including the resin transfer moulding (RTM) method [5, 6]. Concerning the character of this method (a closed two-part stiff mould, liquid resin flow) manufacturers do not usually take into account the application of a gelcoat. Instead of this, the manufactured product is painted with special paints [7, 8]. It is not an ideal solution, especially in case of laminates on a base of natural fibres [9, 10] and ones reinforced with non-crimp structures having deep surface structural inequalities. In such cases, the quality of the surface often negatively affects the mechanical performance of the laminate [11, 12]. A layer of gelcoat may align some of the surface imperfections, eliminating potential notches. An additional significant role which the gelcoat covering may play is shielding the laminate against UV rays. However, the addition of a gelcoat layer may be simultaneously disadvantageous from the point of view of materials mechanics; the areas of layer coupling (interlaminar planes) are often the places where damage occurs first [13], especially when the layer is susceptible to cracking.

The aim of the study is to determine the effect of applying a gelcoat covering on the surface quality and mechanical properties of selected types of glass fibre reinforced polymer (GFRP) laminates produced by the resin transfer moulding (RTM) method. It was assumed that application of the gelcoat improves the surface quality of the laminates (smoothness, lack of gas bubbles) and has a positive effect on their mechanical properties. The presented analyses have a preliminary character and the obtained results may be useful for optimization of the structures and technologies of the laminates.

MATERIALS AND TECHNOLOGICAL PROCEDURE

For purposes of the investigations, a set of laminate panels was manufactured on the basis of three types of glass fibre structures:

1. Plain woven fabric (10 layers, areal mass 320 g/m², produced by KROSSLASS Poland).
2. Chopped strand mat (6 layers, areal mass 540 g/m², produced by KROSSLASS Poland).
3. 3D fabric (7 layers non-crimp, areal mass 3280 g/m², produced by 3TEX, USA).

The panels had the dimensions 320 x 250 mm. They were moulded by the RTM method in a two-part steel mould, at established mould-nest dimensions, ensuring a fibre volume fraction in the manufactured composites in the range of 50÷52%. A vacuum system was applied (without additional pressure on the resin). A scheme of the system is presented in Figure 1. The power of the vacuum pump was 1100 W. The panels were manufactured alternatively without and with an additional gelcoat layer.

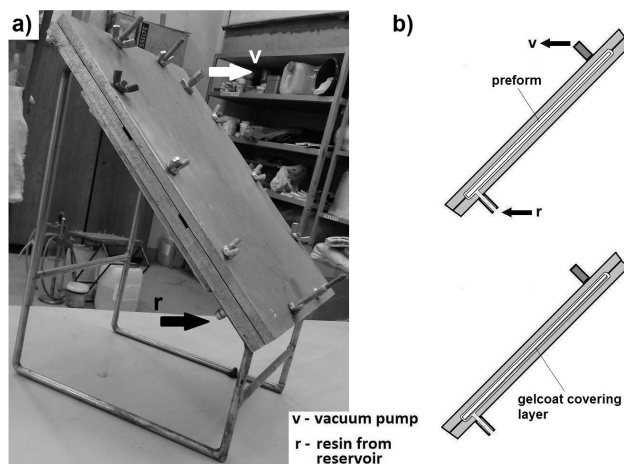


Fig. 1. Scheme of applied RTM system: a) photograph of assembled mould in isometric view, b) side cross-section view of mould and preform without and with gelcoat layer indicated

Rys. 1. Schemat zastosowanego w pracy układu nasycania preform metodą RTM: a) zdjęcie zmontowanej formy, b) widok bocznego przekroju gniazda formy wraz z preformą i zaznaczoną warstwą żelkotu

The gelcoat (polyester-based) was applied with a brush on the nest surface of the lower part of the mould. The surface was covered with the gelcoat until all the lumens disappeared. Each time, the resin flow process was started after the gelcoat had gained an initial cure (rubber consistence). HAVELGEL 2432 polyester gelcoat produced by HAVEL COMPOSITES, Czech Republic, was applied. LH 288 epoxy resin + H 281 hardener (both produced by HAVEL COMPOSITES, Czech Republic) was used as the matrix of the manufactured composites. All the impregnated panels were cured at room temperature for about 20 h and after-cured at 55°C for 4 h. Next, they were acclimatized at room temperature for at least 72 h. The specimens for the tests were cut from the panels with use of a rotating blade.

GELCOAT LAYER EVALUATION METHODS

The basis for evaluating the manufactured laminate surfaces was profilographometric tests. They were conducted using a MICRO PROF optical profilographometer produced by FRT, Germany. A list of descriptions concerning the tested materials is presented in Table 1.

Microscopic visualization was applied in order to evaluate the coupling between the gelcoat layer and the main structure of the laminate. Photographs of the areas at the border line between the gelcoat layer and the main structure of the laminate for all types of specimens were taken with use of a HITACHI S-3400N scanning electron microscope (SEM) equipped with camera. Additionally, in order to provide better contrast between the visualized layers, part of the specimens were photographed with use of a NIKON ECLIPSE 200 MA light microscope in Nomarski's contrast, equipped with a camera.

TABLE 1. Descriptions of shorted names of tested laminates, used in further part of study

TABELA 1. Objasnienia umownych nazw poszczególnych typów laminatów użytych w pracy

Design of laminate type	Description
Plain	Laminate manufactured by RTM method on basis of plain-woven fabric
Plain gelcoat	Laminate manufactured by RTM method on basis of plain-woven fabric with gelcoat layer
Mat	Laminate manufactured by RTM method on basis of chopped strand mat
Mat gelcoat	Laminate manufactured by RTM method on basis of chopped strand mat with gelcoat layer of gelcoat
3D	Laminate manufactured by RTM method on basis of 3D fabric
3D gelcoat	Laminate manufactured by RTM method on basis of 3D fabric with gelcoat layer

To evaluate the effect of the gelcoat layer presence on the mechanical performance of the laminates, static bending tests were performed. They were conducted using an INSTRON 4469 tester, at a loading bar velocity of 10 mm/min and a load head of 5 kN. The conditions of the tests were compatible with the stipulations of the PN-EN ISO 14125 standard. 5 specimens of each type underwent the tests.

RESULTS AND DISCUSSION

The chosen results of the profilographometric analysis are presented in Figures 2-7. They enable comparison of the tested laminates: without and with the gelcoat layer. The profile parameters determined by the profilographometer in accordance to the ISO 25178 standard are listed in Table 2. This enables comparative evaluation of the influence of the gelcoat layer presence on the profile parameters.

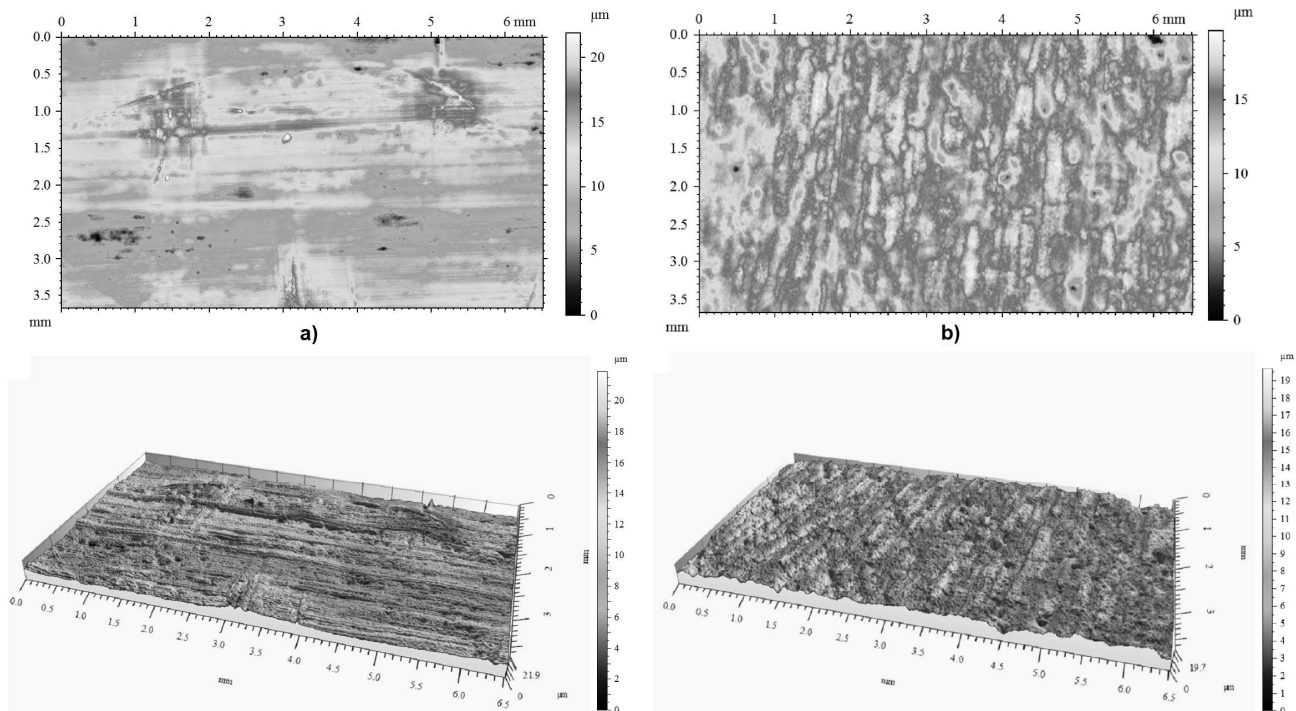


Fig. 2. Isometric image of laminate surface - 2D view (upper) and 3D view (lower): a) plain laminate, b) plain gelcoat laminate

Rys. 2. Izometryczny obraz 2D (górn) oraz 3D (dół) powierzchni badanych laminatów: a) klasyczny, b) klasyczny - żelkot

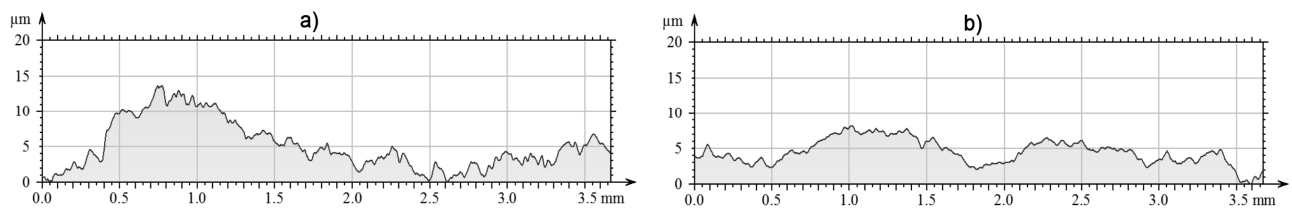


Fig. 3. Roughness distribution on chosen surface area: a) plain laminate, b) plain gelcoat laminate

Rys. 3. Rozkład chropowatości na wybranych obszarach powierzchni laminatów: a) klasycznego, b) klasycznego - żelkot

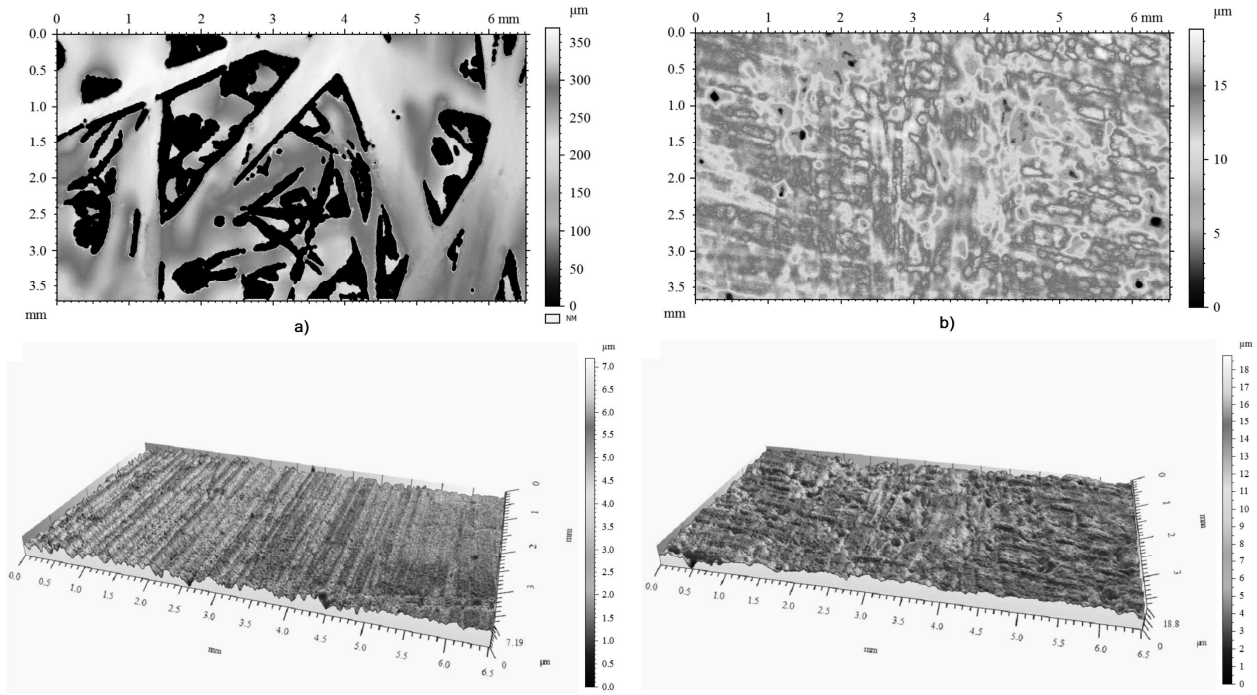


Fig. 4. Isometric image of laminate surface - 2D view (upper) and 3D view (lower): a) *mat* laminate, b) *mat gelcoat* laminate
 Rys. 4. Izometryczny obraz 2D (górn) oraz 3D (dół) powierzchni badanych laminatów: a) mata, b) mata - żelkot

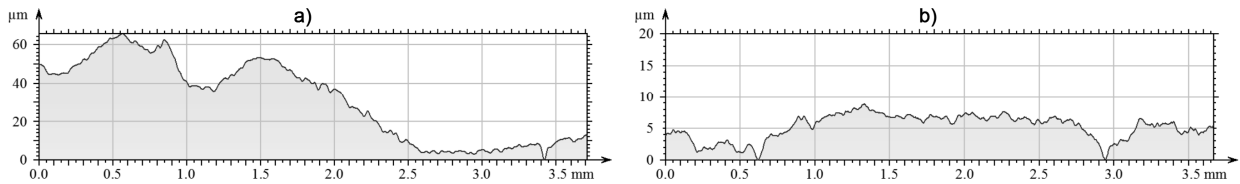


Fig. 5. Roughness distribution on chosen surface area: a) *mat* laminate, b) *mat gelcoat* laminate
 Rys. 5. Rozkład chropowatości na wybranych obszarach powierzchni laminatów: a) mata, b) mata - żelkot

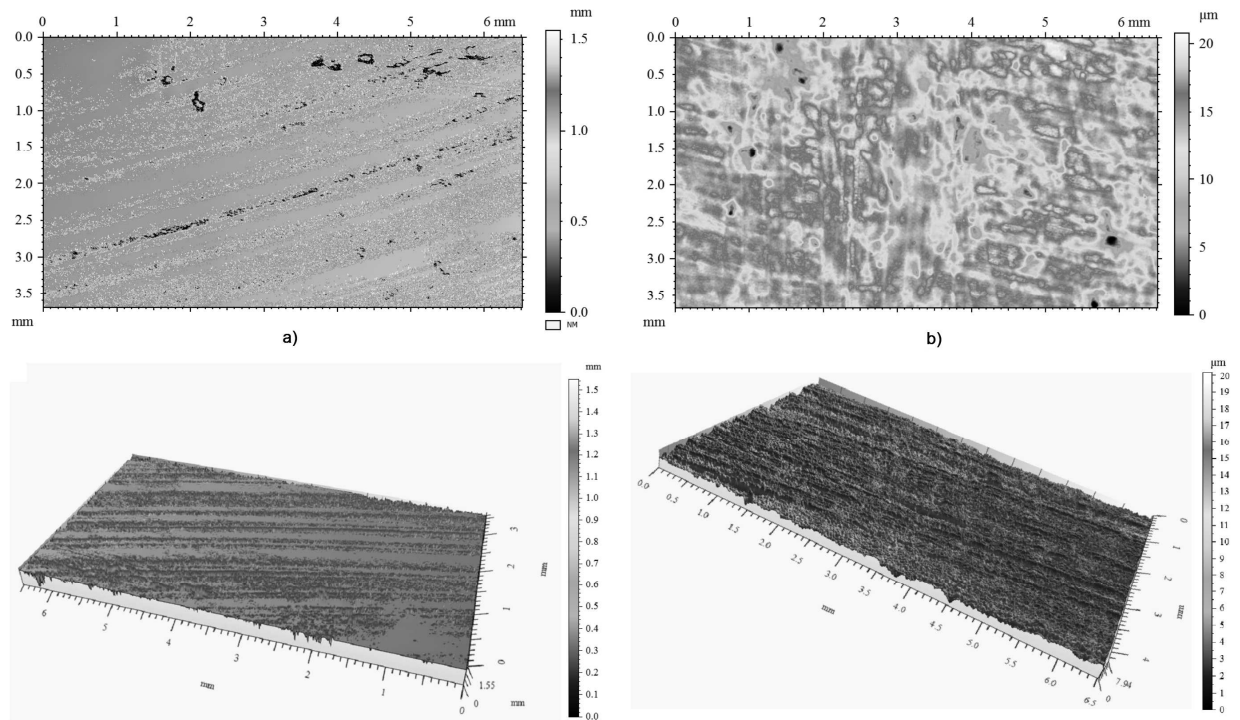


Fig. 6. Isometric image of laminate surface - 2D view (upper) and 3D view (lower): a) 3D laminate, b) 3D gelcoat laminate
 Rys. 6. Izometryczny obraz 2D (górn) oraz 3D (dół) powierzchni badanych laminatów: a) 3D, b) 3D - żelkot

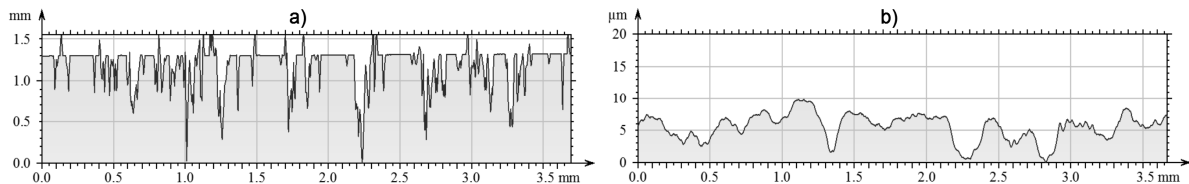


Fig. 7. Roughness distribution on chosen surface area: a) 3D laminate, b) 3D gelcoat laminate

Rys. 7. Rozkład chropowatości na wybranych obszarach powierzchni laminatów: a) 3D, b) 3D - żelkot

TABLE 2. Main surface profile parameters for representative specimens of tested laminates

TABELA 2. Główne 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 surface S_z [μm]*	Arithmetical mean height of surface S_a [μm]*
Plain	11.4	10.5	21.9	2.2
Plain gelcoat	5.34	14.4	19.7	1.73
Mat	156	213	369	124
Mat gelcoat	6.11	12.7	18.8	1.97
3D	388	1160	1550	192
3D gelcoat	7.04	13.7	20.8	2.01

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

The obtained results allow one to conclude that application of the gelcoat covering caused improvement in the surface quality - expressed by a decrease in height of the profile, practically for all the tested specimens. An especially big difference in surface profile height is visible between the 3D laminate without and with the gelcoat layer (Fig. 7, Table 2). The laminates without the gelcoat covering also show a tendency to form an outer resin film reproducing the smooth surface of the mould. Nevertheless, it is not as effective as in case of gelcoat covering - see Figures 3 and 5. 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.

SEM photographs of the gelcoat layer-laminate structure border lines for representative specimens are presented in Figures 8-10.

Additional photographs of the gelcoat layer-laminate structure border line area for two chosen specimens, taken with use of a light microscope in Nomarski's contrast, are presented in Figure 11. There is a more visible contrast between the two bordered layers in these pictures than in the ones taken using SEM.

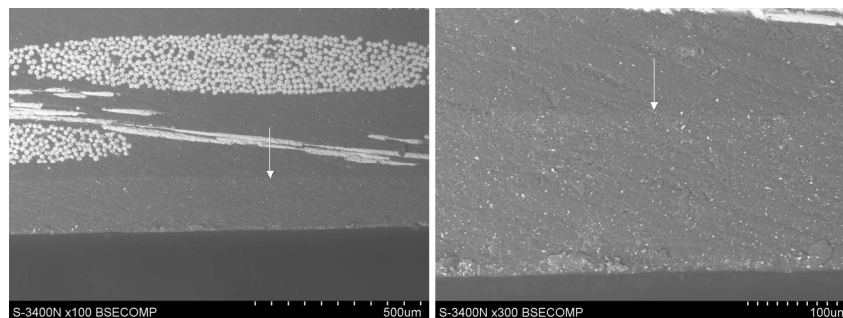


Fig. 8. Laminate *plain gelcoat*: gelcoat layer - laminate structure border line area photographed at two different magnifications. White arrow indicates border line

Rys. 8. Laminat klasyczny - żelkot: linia granicy warstwa żelkotu - zasadnicza struktura laminatu sfotografowana przy dwóch różnych powiększeniach. Biała strzałka wskazuje linię granicy

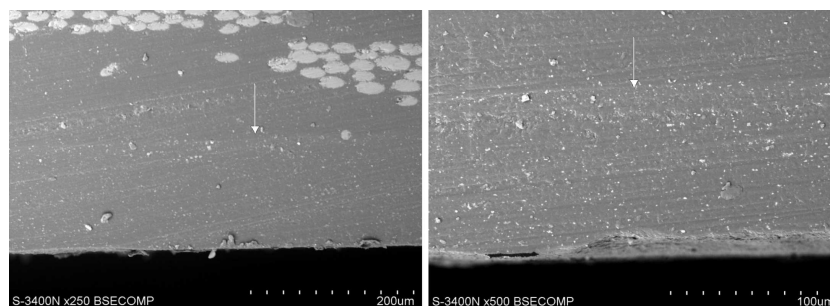


Fig. 9. Laminate *mat gelcoat*: gelcoat layer - laminate structure border line area photographed at two different magnifications. White arrow indicates border line

Rys. 9. Laminat mata - żelkot: linia granicy warstwa żelkotu - zasadnicza struktura laminatu sfotografowana przy dwóch różnych powiększeniach. Biała strzałka wskazuje linię granicy

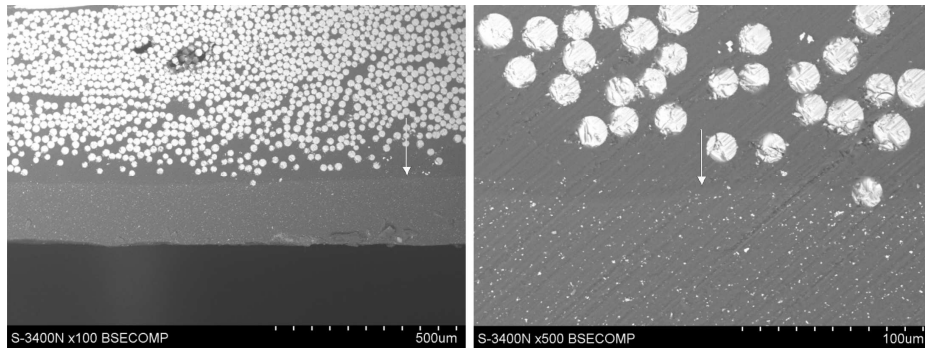


Fig. 10. Laminate 3D gelcoat: gelcoat layer - laminate structure border line area photographed at two different magnifications. White arrow indicates border line

Rys. 10. Laminat 3D - żelkot: linia granicy warstwa żelkotu - zasadnicza struktura laminatu sfotografowana przy dwóch różnych powiększeniach. Biała strzałka wskazuje linię granicy

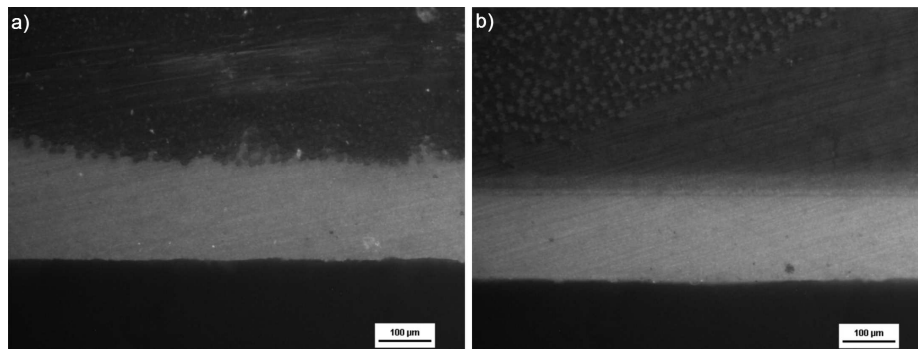


Fig. 11. Photograph taken with light microscope with camera: a) plain gelcoat laminate, b) 3D gelcoat laminate. Border line between gelcoat layer and laminate structure is well visible

Rys. 11. Zdjęcia wykonane podczas obserwacji z użyciem mikroskopu świetlnego: a) laminat klasyczny - żelkot, b) laminat 3D - żelkot. Dobrze widoczna linia granicy między warstwą żelkotu i zasadniczą strukturą laminatu

Practically all the above photographs confirm very good connection in the gelcoat layer-laminate structure border. The transition between these two bordered areas has a rather discrete character. However, a clear diffusive interlayer is visible in the areas where the gelcoat abuts the matrix (Fig. 11b) and penetration of the gelcoat into the fibre strands occurs in areas where the gelcoat layer is close to the strands (Fig. 11a).

Concerning the preliminary character of the study, the mechanical tests were limited only to static bending tests. The results of the tests are presented 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]	Strain at maximum load point ε_{Rg} [%]
Plain	465 ± 55	2.8 ± 0.2
Plain gelcoat	411 ± 18	2.6 ± 0.2
Mat	246 ± 26	3.7 ± 0.3
Mat gelcoat	263 ± 5	3.6 ± 0.1
3D*	466 ± 57	4.9 ± 0.3
3D gelcoat *	454 ± 29	5.0 ± 0.5

* - measured at direction transverse to translaminar interweave strands

The obtained results allow the authors to claim that the presence of the gelcoat layer does not negatively affect the mechanical performance of the tested laminates in a significant way. By analysing together the results of the bending tests (Table 3) and the results of the surface profile heights (Table 2), it may be pointed out that only in the case of the mat and mat gelcoat laminates, the relation the smoother the surface (lower profile height), the higher the flexural strength, is obvious. The rest of the specimens does not show such a trend. It probably arose from the overlap of the two effects of the gelcoat layer presence. The first of them, advantageous, is improvement in the surface quality of the laminate by the gelcoat covering - it contributes to eliminating holes, cavities, notches etc. This effect improves the mechanical performance of the laminate. The second effect, disadvantageous, is the susceptibility of the cured gelcoat to cracking. In such a situation, the presence of even small notches (such a slightly rugged surface is visible in Figures 2, 4 and 6) causes relatively fast occurrence of cracks and their penetration into the main laminate structure. It is a destruction mechanism which quite often occurs in laminates [14, 15] - for example, the presence of a thick resin film on the laminate surface has a very negative effect on its strength. In the case of laminates having a well oriented structure (plain laminate and 3D laminate), the second effect

probably has a greater effect than the first one and it results in a slightly lower strength of the laminates covered with gelcoat in comparison with those not covered. However, the registered differences in strength may arise from other causes, e.g. irregularity in the moulding process (vacuum- and pressure-assisted methods show a very stochastic course [4, 16]), or imperfection in the real structure of the laminate. A significant observation is the fact that all the tested series of specimens with the gelcoat covering showed a significantly lower scatter of results (standard deviation) in comparison with the ones without it - Table 3. It evidently means better repeatability of the mechanical properties of the laminates covered with gelcoat than the classic ones. As an additional conclusion, it may be claimed that the deformability of the tested laminates (Table 3) is not affected by the presence of the gelcoat covering.

As additional mechanical tests, pulling the gelcoat layers out of the laminate main structure was attempted. Nonetheless, the tests did not succeed due to the strong coupling between these two elements. Direct evaluation of the strength of this coupling requires the preparation of special specimens and a special, non-standard measuring method. In fact, these failed tests confirmed that the coupling is very strong.

SUMMARY

The essential conclusion from the performed investigations is that the use of gelcoat does not negatively affect the mechanical performance of laminates manufactured by the RTM method. The consequence of such a conclusion is the statement that RTM technology is very well suited for manufacturing products with gelcoat coverings. It may be applied in a way similar to hand lay-up technologies. The obtained surfaces of the laminates display high quality - even better than those of equivalent laminates without the gelcoat covering. It was also found that improvement of the surface smoothness caused by the presence of the gelcoat covering positively affects the repeatability of the laminate mechanical properties.

Possible continuation of the studies concerning gelcoat coverings on laminates manufactured by pressure-assisted methods should include further mechanical tests (pulling the gelcoat layers out of the laminate main structure, tests of curved panels, impact tests). On a more advanced stage, it also should include manufacturing exemplary comparative products (without and with the gelcoat coverings).

Acknowledgements

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