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COMPOSITES THEORY AND PRACTICE

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COMPARATIVE EVALUATION OF GFRP LAMINATE PANELS MANUFACTURED BY VARI AND RTM METHODS

The aim of the study is a comparative evaluation of panels made of GFRP laminate (10 layers of plain-woven 0/90 glass fabric) by RTM and VARI methods. The evaluation was performed on the basis of the analysis of the laminate thickness, fibre volume fraction and flexural strength. An essential element of the evaluation is the repeatability of the analyzed properties, which is estimated by the standard deviation and coefficient of variation of respectively numerous result series. Comparison of the two mentioned technologies may be significant information concerning their alternative applicability. The range of the study covers: preparation of four reinforcement lay-ups (preforms) of plain-woven glass fabric, manufacturing four laminate panels using the preforms - two by RTM and two by VARI, cutting specimens from the panels, evaluation of the thickness and fibre volume fraction of the specimens, and evaluation of the flexural strength of the specimens in 3-point bending tests. Laminates manufactured by the RTM and VARI methods showed a relatively high reinforcing fibre volume fraction. A slightly higher volume fraction and, at the same time, a significantly smaller thickness were observed in the VARI laminates. The laminates manufactured by RTM showed about a 10% higher flexural strength in comparison with the VARI ones. The laminates manufactured by VARI showed a higher volume fraction but it is probably due to gas voids present in areas near the reinforcing fibre strands. The presence of voids was also proved in the structure of the RTM laminates, but they are of a different nature - they are bigger and are located within the resin-rich areas between the reinforcing layers. The quality of the specimen surface (two-side smoothness in the case of the RTM laminates, one-side smoothness in the case of the VARI ones) could also have some effect on the flexural strength. In the case of both the VARI and the RTM laminates as well, a visible thickness "gradient", directed the from outlet to inlet, was observed. It is caused by "relaxation" of the underpressure after passing of the resin flow front during the impregnation process. The "gradient" is bigger and less uniform in the case of the VARI laminates than in case of the RTM ones. The RTM method occurred to be minimally better than the VARI in terms of repeatability of the fibre volume fraction and flexural strength, measured as the variance coefficient of the results of a specimen series. The worse repeatability of the laminates manufactured by the VARI method results from the bigger laminate thickness "gradient".

Keywords: **laminate, resin transfer moulding (RTM), vacuum assisted resin infusion (VARI), repeatability of properties**

OCENA PORÓWNAWCZA PŁYT Z LAMINATU ŻYWICA POLIESTROWA - TKANINA SZKLANA WYTWORZONYCH METODAMI VARI ORAZ RTM

Celem studium jest ocena porównawcza płyt wykonanych z kompozytu warstwowego żywica poliestrowa - włókno szklane (10 warstw płóciennej tkaniny szklanej) metodami RTM (nasycanie ciśnieniowo-próżniowe) oraz VARI (infuzja próżniowa). Ocena została wykonana na bazie analizy grubości laminatu, udziału objętościowego włókien oraz wytrzymałości na zginanie. Istotnym elementem oceny jest powtarzalność analizowanych właściwości, której miarą jest odchylenie standardowe i współczynnik zmienności odpowiednio dużej serii pomiarów próbek. Porównanie dwóch wymienionych technologii może stanowić istotną informację co do ich alternatywnej stosowalności. Zakres pracy obejmuje: przygotowanie czterech zestawów wzmocnienia (preform) z krzyżowej tkaniny szklanej, wytworzenie na ich bazie płyt - po dwie płyty metodą VARI i RTM, wycięcie próbek, określenie grubości i zawartości objętościowej wzmocnienia w wyciętych próbkach oraz wyznaczenie wytrzymałości na zginanie w trójpunktowej próbie zginania. Laminaty wytworzone metodami RTM oraz VARI wykazały relatywnie wysoki udział objętościowy włókien wzmocnienia. Nieco większy udział włókien oraz znacznie mniejszą grubość uzyskano w laminatach VARI. Laminaty wytworzone metodą RTM wykazały z kolei o ok. 10% większą wytrzymałość na zginanie w porównaniu z laminatami wytworzonymi techniką VARI. Większy udział włókien uzyskany przez laminaty VARI wynika najprawdopodobniej z obecności pustek gazowych w okolicach włókien wzmacniających. Obecność pustek wykazano także w laminatach RTM, jednak mają one inny charakter - są większe i są rozmieszczone w obszarach bogatych w żywicę, między warstwami wzmocnienia. Wpływ na wyniki prób wytrzymałościowych mógł też mieć stan powierzchni laminatów (obustronna gładkość w przypadku laminatów RTM, jednostronna w przypadku laminatów VARI). Zarówno w przypadku laminatów VARI, jak i laminatów RTM wykazano wyraźny „gradient" grubości skierowany w kierunku *od ssania do zasilania*. Jest on spowodowany „relaksacją" podciśnienia po przejściu frontu żywicy w czasie procesu nasycania. „Gradient" jest większy i mniej równomierny w przypadku laminatów VARI niż w przypadku laminatów RTM. Minimalnie lepsza pod względem powtarzalności udziału objętościowego oraz wytrzymałości na zginanie, mierzonej współczynnikiem zmienności serii pomiarów próbek, okazała się metoda RTM. Gorsza powtarzalność płyt wytworzonych metodą VARI wynika z większego „gradientu" grubości.

Słowa kluczowe: **laminat, nasycanie ciśnieniowo-próżniowe (RTM), infuzja próżniowa (VARI), powtarzalność właściwości**

INTRODUCTION

Glass fibre reinforced polymer (GFRP) laminates are increasingly more used in many branches of industry [1-6]. One of the vital technical and research problems concerning this group of materials is the implementation of pressure-assisted (P-A) manufacturing technologies, which (in most cases) replace the traditional lowly-efficient and not eco-friendly hand lay-up techniques [3, 4, 7-10]. The main groups of P-A technologies are: *vacuum assisted resin infusion* (VARI) and *resin transfer moulding* (RTM) [1, 2, 11]. The P-A techniques provide better efficiency and economics of in-series production [8, 9] and better product repeatability [12]. Moreover, the RTM method provides two-side smoothness of the outer surfaces [13]. P-A methods enable efficient joining of elements which often is a problem when applying hand lay-up methods [1, 14, 15]. P-A technologies are also necessary for production using special types of fabrics [16, 17] and for obtaining high-quality products using natural fibres [18]. One of main problems concerning products made of composite laminates is repeatability of the mechanical (and other) properties - it is especially important in the case of responsible structures [19, 20]. Earlier studies of the authors showed that P-A techniques result in better repeatability of the laminate properties than hand lay-up methods [12]. However, a comparative evaluation of the two main P-A techniques (VARI and RTM) seems advisable.

The aim of the study is to evaluate GFRP composite panels manufactured by the RTM and VARI methods. The evaluation was performed on the basis of the analysis of: laminate thickness, fibre volume fraction and flexural strength. A significant element of the evaluation is repeatability of the analyzed properties, which is estimated by the standard deviation and coefficient of variation of respectively numerous result series. Comparison of the two applied P-A technologies may be significant information concerning their alternative applicability, especially in the areas where they are complementary [21, 22].

The range of the study covers: preparation of four reinforcement lay-ups (preforms) of plain-woven glass fabric, manufacturing four laminate panels using the preforms - two by RTM and two by VARI, cutting specimens from the panels, evaluation of the thickness and fibre volume fraction of the specimens and evaluation of the flexural strength of the specimens in 3-point bending tests.

MATERIALS AND METHODS

Plain-woven 0/90 glass fabric, areal mass 320 g/m^2 (according to manufacturer's data), produced by KROSGLASS was used as the reinforcement of the laminates. Sheets of 270 x 200 mm were cut from the bale and laid in a 10-layer stack (0/90). The prepared lay-ups were basted along 15 mm from the edges, producing preforms. The obtained preforms were weighed (together with all single strands of roving which dropped out of the sheets after cutting) and their real areal mass was determined. The measured areal mass of each preform equaled 3070 ±10 g/m^2. The matrix of the composites was polyester resin ESTROMAL 14 LM catalyzed with the LUPEROX K-1 catalyst added in the amount of 2.5% (resin life time 30÷35 min).

Two of the four preforms were impregnated with the resin by the VARI method - a diagram of the process system is presented in Figure 1.

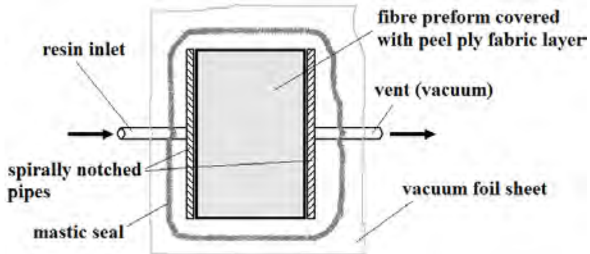

Fig. 1. Diagram of system for vacuum-assisted resin infusion (VARI)

Rys. 1. Schemat układu do nasycania preform metodą VARI

The mould for the VARI process was a flat and smooth steel plate (Fig. 3a). Special wax was used as a release agent and a special mastic was applied to seal the lines of connection between the thermoplastic vacuum-foil and the mould. The preform was separated from the foil with a sheet of special polyamide surface fabric. The inlet and outlet (sucking) channels consisted of T-pipe passing through the foil (sealed opening) and spirally notched pipe, providing a line-shaped flow of resin along the whole width of the preform. The technological stand ready for the VARI process is presented in Figure 4a. Underpressure in the system (mold/preform/foil) was obtained by using an oil vacuum pump TEPRO with an engine power of 1100 W. Tightness tests showed very good tightness of the system in all cases. The pressure gradient at the closed inlet duct was –80 kPa - the same as measured at the output nipple of the pump (no visible difference on a gauge of an accuracy of 2 kPa).

The resin was prepared in a container, in a precisely determined amount, necessary to fill the preform (to the level of 53% by volume) and to provide a slight surplus for filling the inlet spiral pipe. After mixing with the catalyst, the resin was left for 10÷12 minutes for spontaneous degassing in ambient conditions.

After testing system tightness and stabilizing the maximum pressure gradient, the inlet duct was released and the impregnation process started. The time of the process was about 18 min. No structures were applied to accelerate the process - bleeders, nettings, additional transverse pipes. After removal of all the resin from the container, the inlet duct was closed. The underpressure was maintained until the resin was cured within the whole preform (minimum 50 min). After turning off the pump, the cured plates were left in the mould at ambient temperature for about 1 day. Next they were removed from the mould and were post-cured at 55°C for 6 hours and seasoned in ambient conditions for at least 3 days.

Two of the four prepared preforms were impregnated by vacuum assisted resin transfer moulding (RTM). A two-part steel mould was applied for the process, placed obliquely (less than 45°) to the ground - a diagram of the mould is presented in Figure 2.

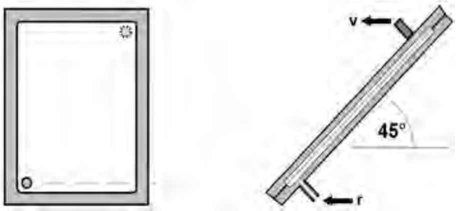

Fig. 2. Diagram of two-part mould (assembled) for RTM process: v - vacuum, r - resin from container

Rys. 2. Schemat formy dwuczęściowej (złożona) do procesu RTM: v - próżnia, r - żywica ze zbiornika

A photo-image of the mould before assemby is presented in Figure 3b. The image of the mould during the process is shown in Figure 4b and the cured preform in the mould cavity - in Figure 4c.

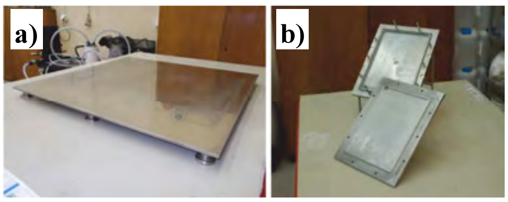

Fig. 3. Laboratory metal moulds for manufacturing panels for tests: a) one-part flat mould for VARI method, b) two-part mould for RTM method

Rys. 3. Laboratoryjne formy metalowe do wytwarzania płyt badawczych: a) metodą VARI - jednoczęściowa, b) metodą RTM - dwuczęściowa

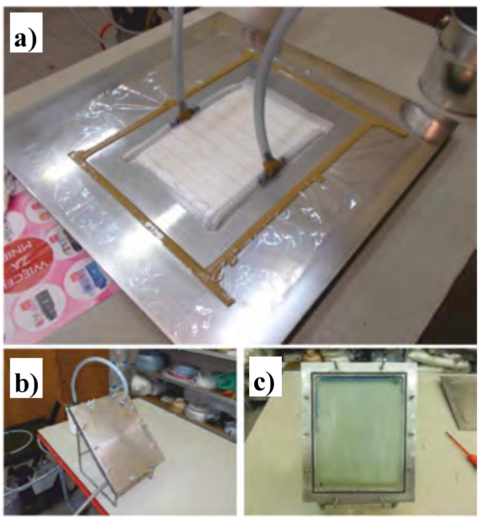

Fig. 4. Manufacturing processes: a) preform ready for VARI process, b) assembled mould during RTM process, c) impregnated and cured panel after RTM process

Rys. 4. Procesy nasycania preform: a) preforma gotowa do rozpoczęcia procesu VARI, b) złożona forma podczas procesu RTM, c) nasycona i utwardzona preforma po procesie RTM

A wax release agent was used. Perfect fit of the preform width to the mould cavity was especially maintained (it allows avoiding air-traps in the manufactured panel). The halves of the mould were assembled with ten M6 screws. Underpressure in the system was obtained by the use of the oil vacuum pump TEPRO with the engine power of 1100 W. The tightness tests - performed analogously as in the VARI case - showed very good tightness of the system. The pressure gradient at the closed inlet duct was –70 kPa. The resin was prepared in a container, in a precisely determined amount necessary to fill the preform (to the level of 50% by volume) and to provide a slight surplus for filling the inlet pipe.

After testing system tightness and stabilizing the maximum pressure gradient, the inlet duct was released and the impregnation process started. The time of the process was about 15 min. After impregnation of the whole preform (occurrence of resin in the outlet pipe), the inlet duct was closed. The underpressure was maintained for the next 1 hour. After turning off the pump, the cured plates were left on the mould in ambient temperature for about 1 day. Next they were removed from the mould and were post-cured and seasoned in the same way as the panels made by the VARI technique.

There was a set of 27 specimens (15 x 60 mm each - according to PN-EN-ISO 14125 standard) outlined on each of the produced panels. The arrangement of the specimens enabled subsequent analysis of the distribution of particular physical characteristics within the panels - Figure 5.

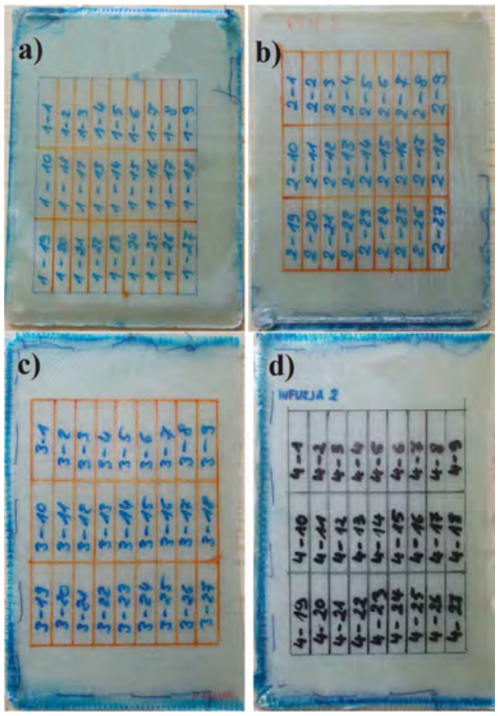

Fig. 5. Panels for testing with outlined sets of specimens: a) and b) panels manufactured by RTM method, designation c) and d) panels manufactured by VARI method

Rys. 5. Płyty badawcze z naniesionym planem rozmieszczenia próbek: a) i b) płyty wytworzone metodą RTM, c) i d) płyty wytworzone metodą VARI

The specimens were cut precisely with the use of a high-speed rotating diamond blade with water-cooling. After the cutting procedure and cleaning, all the specimens were weighed on RADWAG AS 160/C/2 scales with the accuracy of 0.0001 g. The dimensions (width, thickness and length) were measured with the accuracy of 0.02 mm.

The obtained results enabled the authors to easily determine the areal mass of the laminates for individual specimens, which was necessary to calculate the fibre volume fraction according to formula (1):

$$V_w = \frac{\frac{m_w}{\rho_w}}{\frac{m_w}{\rho_w} + \frac{(m_L - m_w)}{\rho_r}} \cdot 100 \qquad (1)$$

where V_w is the reinforcing fibre volume fraction [%], m_w is the areal mass of the reinforcing lay-up (3.07 kg/m^2), [kg/m^2], m_L is the areal mass of the laminate (for an individual specimen it is the mass divided by the ratio of length and width), [kg/m^2], ρ_w is the mass density of the reinforcing fibre material (2540 kg/m^3 was assumed [23]) [kg/m^3], ρ_r is the mass density of the cured resin (1140 kg/m^3 was assumed [23]) [kg/m^3]. The applied method of determining the fibre volume fraction with the use of real areal mass of the fibre lay-up and of the cured laminate is innovative and is a simpler alternative to methods consisting in burning the cured resin from the laminate. The method had already been applied in earlier studies [2, 12] and validated in laboratory conditions. The presented results have a comparative character and not a fundamental one. Static 3-point bending tests were performed on an INSTRON 4469 testing machine, according to the PN-EN-ISO 14125 standard. The loading bar moved at the velocity equaling 5 mm/min, and the spacing of the supporting bars was 48 mm.

RESULTS AND ANALYSIS

The results of the tests for individual specimens sets are presented in Table 1.

TABLE 1. **Measured properties of laminates manufactured by RTM and VARI methods**

TABELA 1. **Zmierzone właściwości laminatów wytworzonych metodami RTM oraz VARI**

Manufacturing method	Panel thickness [mm]	Reinforcing fibre volume fraction [%]	Flexural strength [MPa]
RTM 1	2.70 ± 0.06 (2.0%)*	54.8 ± 1.5 (2.7%)	246 ± 18 (7.4%)
RTM 2	2.75 ± 0.06 (2.3%)	51.9 ± 2.0 (3.9%)	264 ± 24 (9.2%)
RTM (1 + 2)	2.72 ± 0.06 (2.3%)	53.3 ± 2.3 (4.3%)	255 ± 23 (9.1%)
VARI 1	2.51 ± 0.10 (3.8%)	63.1 ± 3.3 (5.2%)	232 ± 22 (9.3%)
VARI 2	2.54 ± 0.12 (4.6%)	59.8 ± 4.1 (6.9%)	218 ± 20 (9.4%)
VARI (1 + 2)	2.53 ± 0,11 (4.3%)	61.4 ± 4.0 (6.6%)	225 ± 22 (9.8%)
* - values in brackets - variation coefficients			

The fibre volume fraction is higher by about 8% for the laminates manufactured by the VARI method (Table 1). It corresponds to the thickness of the laminates - the VARI laminate is by about 7% thinner than the RTM one. The main reason for the difference in thickness and in fibre volume fraction for the laminates is probably the pressure of the foil on the preform, caused by the underpressure, which occurs in the VARI process. The pressure inhibits surplus resin collecting in the interlaminar areas of the preform. The structure images of the laminates manufactured both by the RTM and VARI methods are shown in Figure 6.

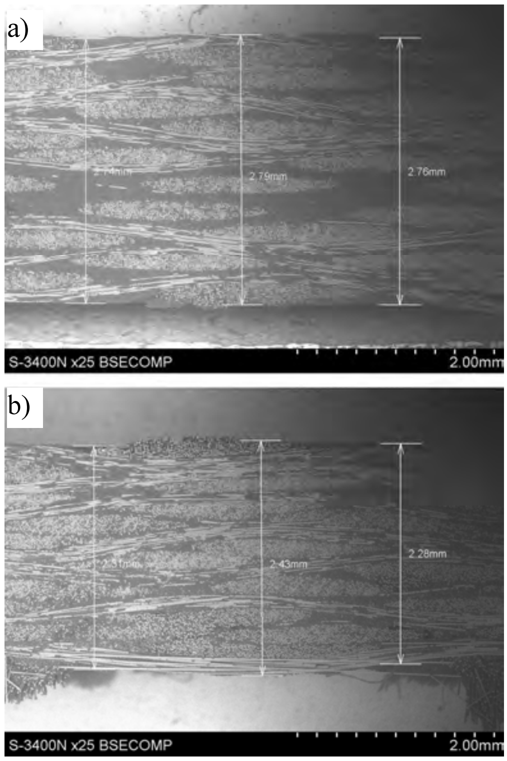

Fig. 6. SEM images of laminate structure at 25x magnification: a) laminate manufactured by RTM, b) laminate manufactured by VARI

Rys. 6. Obrazy SEM struktury laminatów przy powiększeniu 25x: a) laminat wytworzony metodą RTM, b) laminat wytworzony metodą VARI

The difference in thickness is clearly visible. The images were performed using a scanning electron microscope (SEM) HITACHI S-3400N, in low-vacuum conditions.

However, the laminates manufactured by RTM showed about a 12% higher strength than the VARI ones (Table 1), despite the lower volume fraction. Such results are surprising because according to the rule of mixtures, the strength of the composite should increase with an increasing reinforcing phase fraction [1, 7, 23-25]. The observed behavior probably results from the presence of small gas voids in the laminate structure. An image of the RTM laminate structure is presented in Figure 7, and of the VARI laminate - in Figure 8.

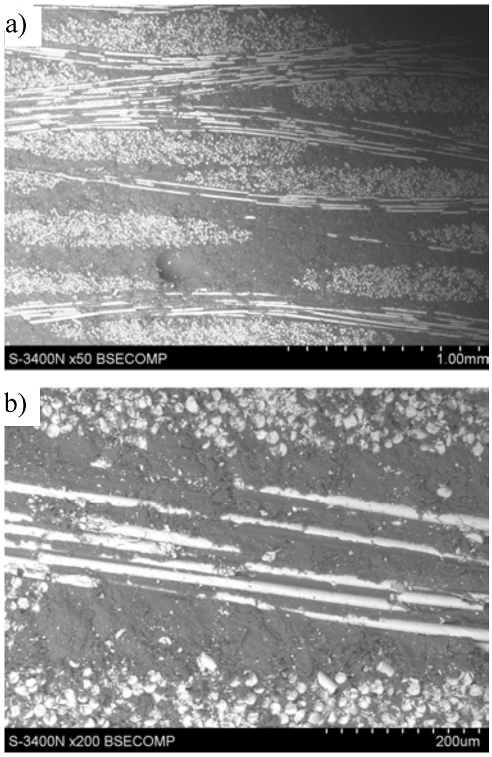

Fig. 7. SEM image of structure of laminate manufactured by RTM: a) magnification 50x, visible gas void of about 0.2 mm in diameter, b) magnification 200x - structure is "clear"

Rys. 7. Obraz SEM struktury laminatu wytworzonego metodą RTM: a) powiększenie 50x, widoczny pęcherz gazowy o średnicy ok. 0,2 mm, b) powiększenie 200x - „czysta" struktura

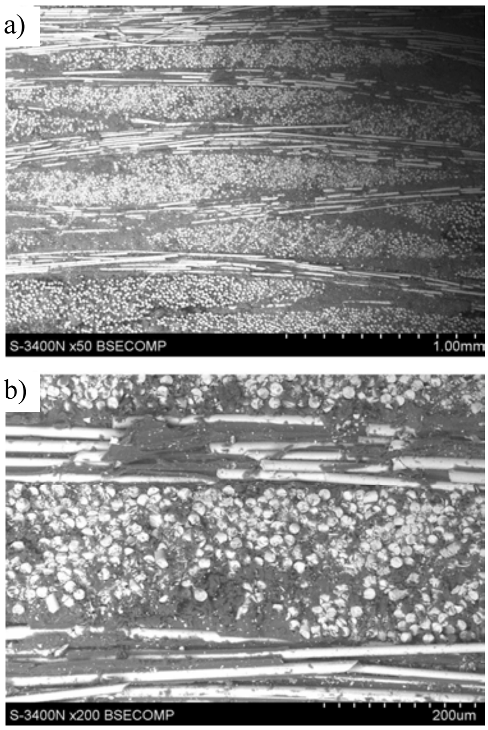

Fig. 8. SEM image of structure of laminate manufactured by VARI: a) magnification 50x, b) magnification 200x, quite numerous gas voids of 10÷50 μm in diameter visible, situated mainly around strands of reinforcing fibres

Rys. 8. Obraz SEM struktury laminatu wytworzonego metodą VARI: a) powiększenie 50x, b) powiększenie 200x, widoczne dość liczne pustki gazowe o wymiarach rzędu 10÷50 μm rozmieszczone głównie w okolicach włókien

It is visible in the SEM images that in the case of the RTM laminate, the gas-voids have an agglomerated character and they occur in the resin-rich areas between the reinforcing layers. These areas are quite thick in RTM laminates. In the VARI laminate the voids are scattered and located near the reinforcing fibre strands. It is probably connected with the limited possibility of flow of the relatively highly-viscous (about 1000 mPa·s) resin, caused by the pressure of the vacuum-foil. In order to analyze the effect of foil pressure on the presence and distribution of voids, additional study would be necessary with the use of a low-viscosity resin. The possible reasons for the occurence of the voids are: 1) introduction of air to the resin during mixing with the catalyst, 2) evaporation of styrene which is an ingredient of liquid resin. The very good seal of the vacuum system (pump, mould, ducts) restricts the possibility of air introduction due to leaks. Reliable care of assembly and sealing is at least comparable with that achieved in industrial conditions (maybe excluding high-efficient RTM systems equipped with hydraulic servomotors for sealing of the moulds). Therefore, one should expect similar problems during industrial manufacturing of FRP laminate products.

Precise analysis of the tightness (for both RTM and VARI methods) would demand additional research with the use of acoustic sensors. It would allow the authors to discover whether a leak in the vacuum system contributes to introducing gas voids to laminate structures.

The voids caused by styrene evaporation are quite probably due to the fact that near the resin flow front some amount of styrene is exposed to decreased pressure for some period of time, which leads to reflux (intensive evaporation).

The other element affecting the flexural strength of the laminates may be the condition (quality) of the panel surface. In theory, the outer surfaces of tested specimens are the most strained during bending load [26]. In the case of the RTM laminates two-side smoothness is gained. At the same time, the VARI laminates are only one-side smooth. It should be emphasized that in all the bending tests performed on the VARI laminate, the specimens were placed with the smooth side on the supports.

Furthermore, the thickness of the specimens affects the flexural strength (though it is involved in the flexural stress formula [26]), and there is about a 10% difference between the RTM and the VARI laminates. A precise definition of the reasons for the determined differences in flexural strength between the RTM laminates and the VARI ones would demand a separate comprehensive research study. It should be emphasized that the obtained flexural strength values (Table 1) are high enough to regard the tested laminates as valuable constructional material. Moreover, the difference in flexural strength between the RTM laminates and the VARI ones (about 10%) is also close to insignificance. The measures of the repeatability of volume fraction and flexural strength of the tested laminates, which are the standard deviation and coefficient of variation, show that the RTM method shows better repeatability of the manufactured laminates (Table 1). The standard deviation of the fibre volume fraction for the laminates manufactured by the VARI method is almost 2 times higher than that of the RTM ones. It is probably caused by big dispersion of the panel thickness in the case of the VARI laminates due to the "gradient" - significantly bigger than in case of the RTM laminates. The "gradient" occurs from relief of the underpressure after passing of the resin flow front which causes a bigger inflow and collecting of the resin in the area close to the inlet line. This phenomenon has already been observed in VARI processes [2, 12]. However, the thickness gradient is also observed in the RTM laminates. It is obvious when comparing the results of individual panel sectors (diagram in Fig. 9) shown in Tables 2 and 3.

The most likely reasons for the thickness "gradient" in the case of the RTM laminates (possible inaccuracy of the mould cavity was checked and eliminated by experimental evaluation of the laminates manufactured at two alternative outlet/inlet directions: ±45°) are "squeezing" of the fibre strands within the area close to the inlet caused by the gravity-mould placed less than 45°, and the high mass density of the glass fibres. As in the VARI process, underpressure occurs before the resin flow front and after the passing of it, the underpressure is subjected to gradual "relaxation". Comparison of the results in Tables 3 and 2 indicates that in the case of the RTM panels, the increases in thickness of individual sectors ("gradient" in the direction *from inlet to outlet*) are lower and more uniform than those of the VARI ones. The mould in the RTM process is stiff, which forces uniform pressure on the preform. Such behavior does not occur in the VARI process due to the elastic foil representing the upper part of the mould.

Concerning repeatability of the thickness and fibre volume fraction, the panels obtained by the RTM and VARI method are rather comparable. In the case of the RTM method, the variation coefficient for the volume fraction is 4.3% and for VARI - 6.6% (Table 1).

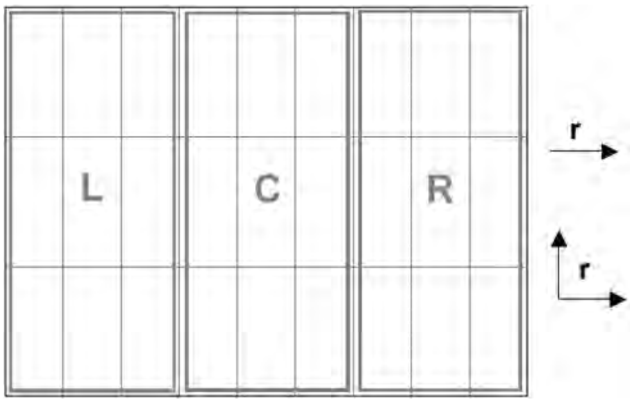

Fig. 9. Adopted partition of laminate panels into sectors for needs of analysis: L - left, C - central, R - right, r - resin flow direction

Rys. 9. Umowny podział płyt laminatowych na sektory, na potrzeby analizy: L - lewy, C - centralny, R - prawy, r - kierunek przepływu żywicy.

TABLE 2. **Fibre volume fraction and thickness of different laminate sectors (Fig. 9) manufactured by RTM method**

TABELA 2. **Udział objętościowy włókien oraz grubość różnych obszarów laminatów (rys. 9) wytworzonych metodą RTM**

Plate	Laminate sector	Laminate thickness [mm]	Fibre volume fraction [%]
1	Left	2.72 ± 0.05	54.2 ± 0.9
	Central	2.71 ± 0.04	54.6 ± 0.9
	Right	2.68 ± 0.07	55.7 ± 0.8
2	Left	2.80 ± 0.05	51.5 ± 1.6
	Central	2.75 ± 0.04	51.4 ± 1.1
	Right	2.68 ± 0.04	52.7 ± 0.6
1 + 2	Left	2.76 ± 0.05	52.8 ± 1.2
	Central	2.73 ± 0.04	53.0 ± 1.0
	Right	2.68 ± 0.05	54.2 ± 0.7

TABLE 3. **Fibre volume fraction and thickness of different laminate sectors (Fig. 9) manufactured by VARI method**

TABELA 3. **Udział objętościowy włókien oraz grubość różnych obszarów laminatów (rys. 9) wytworzonych metodą VARI**

Plate	Laminate sector	Laminate thickness [mm]	Fibre volume fraction [%]
1	Left	2.58 ± 0.09	59.7 ± 1.5
	Central	2.48 ± 0.08	63.5 ± 1.1
	Right	2.48 ± 0.08	66.0 ± 0.7
2	Left	2.67 ± 0.09	54.7 ± 1.2
	Central	2.52 ± 0.04	61.3 ± 0.9
	Right	2.44 ± 0.08	63.3 ± 0.8
1 + 2	Left	2.63 ± 0.09	57.2 ± 1.4
	Central	2.50 ± 0.06	62.4 ± 1.0
	Right	2.46 ± 0.08	64.7 ± 0.8

Therefore, RTM gives a slightly better repeatability than ARI. It does not translate directly to the difference in the variance coefficient of flexural strength - it is 9.1% for RTM and 9.8% for VARI. The difference is only minimal in this case. Furthermore, the differences within the methods themselves are quite stable - see the results in Table 1. The biggest "instability" is shown by the flexural strength for the RTM panels (7.4 and 9.2%). However, it should be emphasized that flexural stress is affected by stochastic factors (specimen surface quality, accidental notches, presence and distribution of voids in the structure). Moreover, the standard deviation applied as the measure of error is "sensitive" even for single results further from the average value.

CONCLUSIONS

1. Laminates manufactured by RTM and VARI methods showed a relatively high reinforcing fibre volume fraction. A slightly higher volume fraction and, at the same time, a significantly lower thickness

were obtained in the VARI laminates. The laminates manufactured by RTM showed about a 10% higher flexural strength in comparison with the VARI ones.

2. The differences in flexural strength are not correlated with the differences in fibre volume fraction. The laminates manufactured by VARI showed a higher volume fraction but it is probably owing to gas micro-voids present in areas near the reinforcing fibre strands. The presence of voids was also proved in the structure of the RTM laminates, but they are of a different nature - they are bigger and are situated within the layers of resin between the reinforcing layers. The quality of a specimen surface (two-side smoothness in case of the RTM laminates, one-side smoothness in the case of the VARI ones) could also have some effect on the flexural strength.
3. In the case of both the VARI and the RTM laminates, a visible thickness "gradient" directed *from outlet to inlet* was observed. It is caused by "relaxation" of the underpressure after passing of the resin flow front during the impregnation process. The "gradient" is bigger and less uniform in the case of the VARI laminates than the RTM ones.
4. The RTM method occured to be minimally better than the VARI in terms of repeatability of fibre volume fraction and flexural strength, measured as the variance coefficient of specimen series results. Worse repeatability of the laminates manufactured by the VARI method results from the larger laminate thickness "gradient".

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REFERENCES

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

[2] Kozioł M., Rydarowski H., Wytwarzanie wyrobów z laminatów żywica utwardzalna - włókno na przykładzie łopaty wentylatora przemysłowego, Główny Instytut Górnictwa, Katowice 2014.

[3] Mrówczyński K., Kompozyty polimerowe - branża z przyszłością, Chemia i Biznes 2012, 6.

[4] Jarosik A., Rynek kompozytów będzie wzrastał, Chemia i Biznes 2013, 3.

[5] Sen R., Mullins G., Application of FRP composites for underwater piles repair, Composites Part B 2007, 38, 5-6, 751-758.

[6] Van Den Einde L., Zhao L., Seible F., Use of FRP composites in civil structural applications, Construction and Building Materials 2003, 17, 6-7, 389-403.

[7] Królikowski W., Kłosowska-Wołkowicz Z., Penczek P., Żywice i laminaty poliestrowe, WNT, Warszawa 1986.

[8] Kozioł M., Budziński M., Opłacalność produkcji wyrobów kompozytowych, Ekonomika i Organizacja Przedsiębiorstwa 2014, 774, 7, 107-120.

[9] Reuterlov S., Cost effective infusion of sandwich composites for marine applications, Reinforced Plastics 2002, 12, 30-34.

[10] Marsh G., Resin film infusion - composites cost reducer, Reinforced Plastics 2002, 2, 44-49.

[11] Williams C., Summerscales J., Grove S., Resin infusion under flexible tooling (RIFT): a review, Composites Part A 1996, 27, 7, 517-524.

[12] Rydarowski H., Kozioł M., Repeatability of glass fiber reinforced polymer laminate panels manufactured by hand lay-up and vacuum-assisted resin infusion, Journal of Composite Materials 2015, 49, 5, s. 573-586.

[13] Kozioł M., Śleziona J., Charakterystyka płyt kompozytowych wytworzonych metodą RTM ze zszywanych preform włókna szklanego, Inżynieria Materiałowa 2008, 2, 109-113.

[14] Rutecka M., Kozioł M., Myalski J., Wpływ wypełniacza z recyklatu poliestrowo-szklanego na właściwości mechaniczne laminatów, Kompozyty 2006, 6, 4, 41-46.

[15] Kozioł M., Myalski J., Bogdan A., Wytwarzanie kompozytów warstwowych metodą RFI, Kompozyty 2009, 9, 3, 265--270.

[16] Kozioł M., Effect of thread tension on mechanical performance of stitched glass fibre-reinforced polymer laminates - experimental study, Journal of Composite Materials 2013, 47, 16, 1919-1930.

[17] Verijenko B., Verijenko V., Smart composite panels with embedded peak strain sensors, Composite Structures 2003, 62, 3-4, 461-465.

[18] Bogdan-Włodek A., Kozioł M., Myalski J., Influence of surface treatment on the wetting process of jute fibres with thermosetting polyester resin, Polish Journal of Chemical Technology 2012, 14, 1, 21-27.

[19] Lopes C.S., Gurdal Z., Camanho P.P., Tailoring for strength of composite steered-fibre panels with cutouts, Composites Part A 2010, 41, 12, 1760-1767.

[20] Roussos L.A., Powell C.A., Grosveld F.W., Koval L.R., Noise transmission characteristics of advanced composite structural materials, Journal of Aircraft 1984, 21, 7, 528--535.

[21] http://www.moldedfiberglass.com/sites/default/files/docs/MFG_Selecting_FRP_Composite_for_Projects.pdf (access 29.10.2015).

[22] https://www.youtube.com/watch?v=v86--QI0xq8 (access 29.10.2015).

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

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

[25] Boczkowska A. i in., Kompozyty, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2003.

[26] Dyląg Z., Jakubowicz A., Orłoś Z., Wytrzymałość materiałów tom I, WNT, Warszawa 2013.