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COMPOSITES THEORY AND PRACTICE

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ASSESSMENT OF VACUUM BAG PRESSURE IMPACT ON POROSITY OF LAMINATES MADE WITH VBO PREPREGS

Vacuum bag only (VBO) prepregs allow for manufacturing composite airframe parts without the need for expensive autoclaves since such prepregs can be cured in ovens with the help of vacuum bags. However, the vacuum pressure must be kept at an acceptable level to obtain low porosity products. One of such prepregs is Cytec MTM46/HTS(12K)-150-35% RW carbon/epoxy VBO prepreg designed for airframe applications. The aim of the presented research was to determine an acceptable level of vacuum pressure in vacuum bags, in particular, and the effect it exerts on the porosity of laminates made with the aforementioned prepreg. For this purpose, UD laminate plates were manufactured under 10, 40, 60, 80 kPa and 96kPa vacuum pressure. Next, ultrasound attenuation displayed by every single plate during ultrasound C-scanning was defined in terms of the so-called full screen height percentage and presented in the form of coloured contour plots. Upon counting the pixels corresponding to each colour, it was possible to determine plate area fractions for each attenuation level. Next, a certain number of specimens was cut out of the plate regions that differed in their attenuation and these specimens were x-rayed with the help of a tomograph, then specialized software was used to determine their porosity. Finally, an experimental relationship between the ultrasound attenuation and specimen porosity was determined.

Keywords: porosity, VBO prepregs, ultrasound attenuation

OSZACOWANIE WPŁYWU CIŚNIENIA W WORKU PRÓŻNIOWYM NA POROWATOŚĆ WYROBU Z PREIMPREGNATU TYPU VBO

Tak zwane „vacuum bag only" (VBO) preimpregnaty umożliwiają wytwarzanie struktur lotniczych bez potrzeby stosowania autoklawów. Prepregi takie mogą być utwardzane w piecach, z wykorzystaniem worków próżniowych. Jednakże, by uzyskać porowatość na akceptowalnym poziomie, ciśnienie w worku próżniowym musi być utrzymywane na odpowiednio niskim poziomie. Przedstawione badania dotyczą wpływu, jakie wywiera podciśnienie w worku próżniowym na porowatość wyrobu. W celu zbadania tej zależności wykonano jednokierunkowo wzmocnione płyty z wykorzystaniem prepregu VBO MTM46/HTS(12K)-150-35% RW firmy Cytec. Płyty utwardzano, stosując podciśnienia 10, 40, 60, 80 i 96 kPa, a następnie, wykonując C-skany, wyznaczono tłumienie sygnału ultradźwiękowego dla każdej z płyt. Jako miarę tłumienia przyjęto wielkość amplitudy odbitego sygnału wyrażoną w procentach wysokości ekranu skanera (w funkcji tzw. FSH). Uzyskane wyniki przedstawiono w formie kolorowych map warstwicowych. Licząc pixele odpowiadające każdej z barw, wyznaczono stosunki pól o wyselekcjonowanych wartościach tłumienia w odniesieniu do całkowitej powierzchni analizowanych płyt. Następnie, wykorzystując tomografię komputerową i specjalistyczne oprogramowanie, wyznaczono porowatości próbek wyciętych z wytypowanych obszarów badanych płyt. Umożliwiło to uzyskanie doświadczalnej zależności między tłumieniem fali ultradźwiękowej w badanym laminacie a jego porowatością.

Słowa kluczowe: porowatość, prepregi VBO, tłumienie fal ultradźwiękowych

INTRODUCTION

Recently, prepregs with resin systems that can be cured out of autoclaves, called vacuum bag only (VBO) prepregs, have become available on the market. Probably the most common suppliers of such products are TanCate [1] and Cytec [2] providing the 8020, E644, E650 and MTM family of prepregs, respectively. The main advantage of VBO prepregs over traditional ones is that the former can be cured with the use of vacuum bags only and in ovens which are much less expensive than autoclaves (Fig. 1). However, curing laminates out of an autoclave without high external pressure makes the control of their porosity difficult. In the case of autoclave curing, in its initial stage volatile components of resin systems, e.g. solvent residuals, come out of the resin and grow due to a temperature rise (Fig. 2b).

The application of high autoclave pressure suppresses pore formation and reduces the size of already formed pores. In the case of oven curing, the hydrostatic pressure in the resin does not exceed the atmospheric one which is lower than the partial pressure of volatiles at curing temperature. To circumvent this inconvenience, a special technique for fiber impregnation was developed. It consists in placing dry reinforcement between two partially cured resin films and pressing them into reinforcement with a system of rollers. This process eliminates the solvent and in addition leaves free spaces between the fibers for air evacuation. Nevertheless, some air still remains between the fibers and individual plies, and expands with temperature (Fig. 2a).

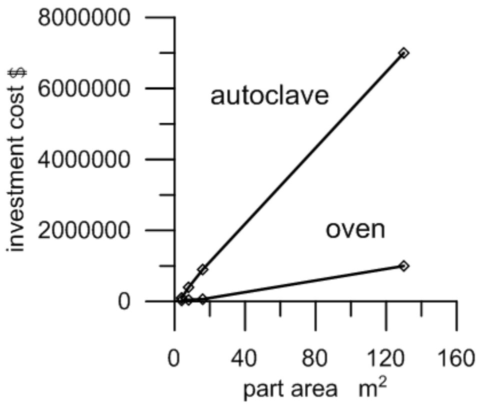


Fig. 1. Investment cost of autoclaves and ovens versus cured part area [3]

Rys. 1. Koszt autoklawu i pieca w odniesieniu do powierzchni utwardzanego wyrobu [3]

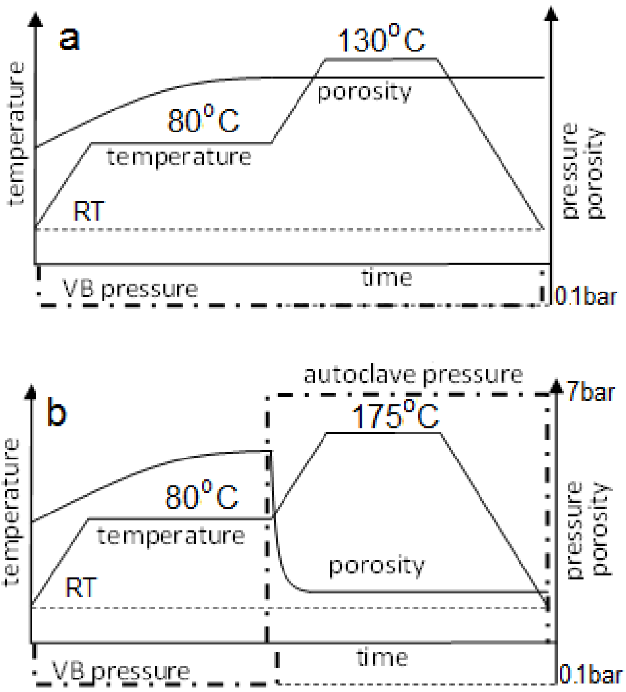


Fig. 2. Typical temperature-time and pressure-time diagrams with porosity variation overlaid: a) VBO prepreg system, b) autoclave cured prepreg system

Rys. 2. Typowe zależności temperatura-czas z nałożonymi zmianami porowatości: a) VBO prepreg, b) prepreg utwardzany w autoklawie

Since the resin hydrostatic pressure can not be increased above the atmospheric one, the pore size cannot be reduced during consecutive curing stages. The intensity of air evacuation depends on several factors.

The most important are:

1. the difference between the resin hydrostatic pressure resulting from the out-of-bag atmospheric pressure and the vacuum pressure produced by the vacuum system,
2. the time left for air evacuation which depends on the intensity the resin fills the free space between individual fibers closing in this way the air evacuation ducts (drop in resin viscosity is a function of both the temperature and the temperature rise gradient).

The authors focused on the first of the aforementioned factors By analysing the Time-Temperature-Transformation diagram, it is clear that the low vacuum pressure inside a vacuum bag should be kept until resin vitrification, however, an accidental malfunction of the vacuum system or leakage of the vacuum bag can result in not meeting this condition. In such circumstances, a question arises about what decision should be done with the respect to the cured product. To answer it, one should know how the recorded vacuum pressure drop affected the laminate porosity. One of the ways to asses laminate porosity is to investigate the changes in ultrasound attenuation [4-7] observed in the impulse-echo ultrasound product inspection and relate it to the varying porosity which in turn can be related to certain mechanical properties of the laminate. The presented research is in progress and for this reason the provided information is limited to the correlation between the vacuum level maintained for each plate during its curing and ultrasound attenuation (UA) of a plate. Furthermore, the initial results obtained from a limited number of specimens relating UA to porosity determined with the help of computed tomography are provided.

EXPERIMENTAL PROCEDURE

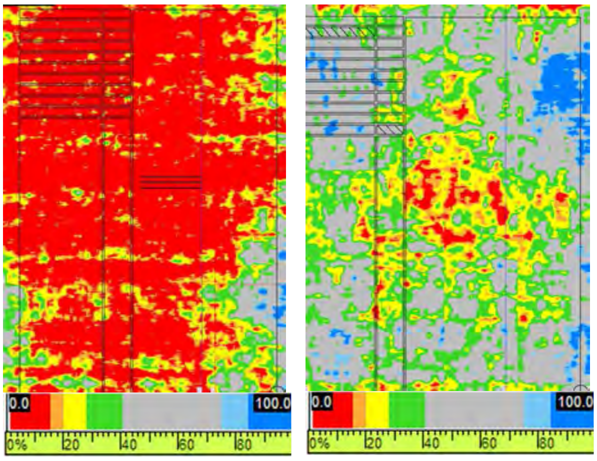
Specimens

The specimens were in the form of unidirectional 300x200 mm laminate plates consisting of 20 layers of Cytec MTM46/HTS(12K)-150-35% RW carbon/epoxy VBO prepreg. The reinforcement direction was kept parallel to the shorter plate edges. In the course of stacking, for every four consecutive ply placements, 15 minutes of debulking was applied. The plates were cured at 135°C for 90 minutes. The following vacuum pressures were maintained during the whole curing process for each individual plate: 10, 40, 60, 80 and 96 kPa, respectively.

Ultrasound testing

The C-scan tests were carried out with the help of the OmniScan Phased Array MX 128:32 system equipped with a 5L64-64X-NW1-P-2.5-OM *f* = 5 MHz probe. The obtained results were in the form of contour plots (Figs. 3-5), representing UA in fractions of the full screen height (FSH), where the FSH signal corresponded to the attenuation obtained for specimens with a porosity ≤ 1% (porosity was defined as the fraction of voids over the volume of the specimen the voids were included in). Seven fractions of FSH were selected:

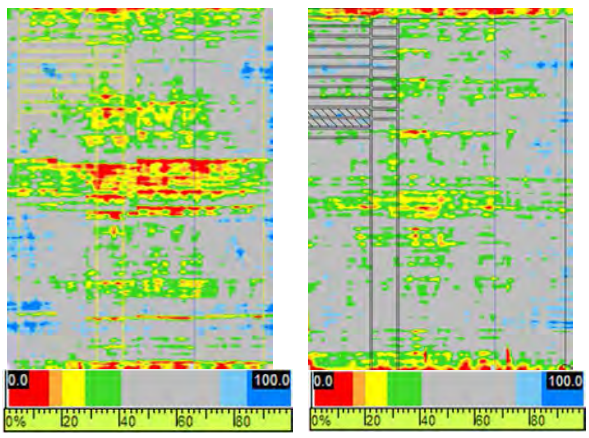
- 0÷16% FSH (in red), corresponding to the echo amplitude drop ≥ 14 dB,
- 16.01÷20% FSH (in light red), corresponding to the echo amplitude drop in the range –12 dB to –14 dB,
- 20.01÷28.5% FSH (in yellow), corresponding to the echo amplitude drop in the range –9 dB to –12 dB,
- 28.51÷40% FSH (in green), corresponding to the echo amplitude drop in the range –6 dB to –9 dB,
- 40.01÷75% FSH (in gray), corresponding to the echo amplitude drop below 6 dB,
- 75.01÷85% FSH (in light blue),
- 85.01÷100% FSH (in blue).



vacuum pressure 10 kPa vacuum pressure 40 kPa

Fig. 3. Contour plots of UA expressed in terms of FSH for 10 and 40 kPa vacuum pressures

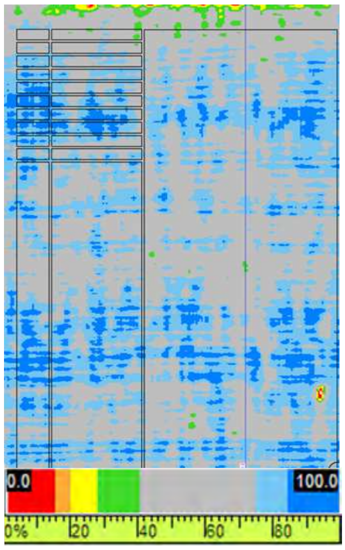
Rys. 3. Wykres warstwicowy tłumienia fali ultradźwiękowej przez płyty wykonane z zastosowaniem podciśnienia 10 i 40 kPa. Tłumienie wyrażone w FSH



vacuum pressure 60 kPa vacuum pressure 80 kPa

Fig. 4. Contour plots of UA expressed in terms of FSH for 60 and 80 kPa vacuum pressures

Rys. 4. Wykres warstwicowy tłumienia fali ultradźwiękowej przez płyty wykonane z zastosowaniem podciśnienia 60 i 80 kPa. Tłumienie wyrażone w FSH



vacuum pressure 96kPa

Fig. 5. Contour plots of UA expressed in terms of FSH for 96 kPa vacuum pressure

Rys. 5. Wykres warstwicowy tłumienia fali ultradźwiękowej przez płyty wykonane z zastosowaniem podciśnienia 96 kPa. Tłumienie wyrażone w FSH

Determination of porosity

To determine laminate porosity and relate it to the UA of certain plate regions, 3 mm x15 mm specimens were cut out from selected regions of the scanned plates and x-rayed with the help of a tomograph, then the void volume was calculated for each specimen with the specialized software and the volume fraction was calculated. A general description of this method can be found e.g. in [8].

Data reduction of attenuation measurements

To gain more precise knowledge on how vacuum pressure affected plate UA, the plate area fractions displaying the selected UA were calculated. For this purpose, the numbers of pixels creating every single contour plot were determined and related to the total number of pixels representing the entire plate image under consideration.

RESULTS

Figures 3-5 present the contour plots of UA expressed in terms of FSH for laminates cured with the help of vacuum pressure equal to 10, 40, 60, 80 and 96 kPa, respectively.

The contour of the cut-out specimens have been overlaid on the FSH contour plots. The bar plots in Figures 6-8 present the plate area fractions corresponding to the considered FSH fractions. The relationship representing porosity versus FSH based on a limited number of initial tests is presented in Figure 9.

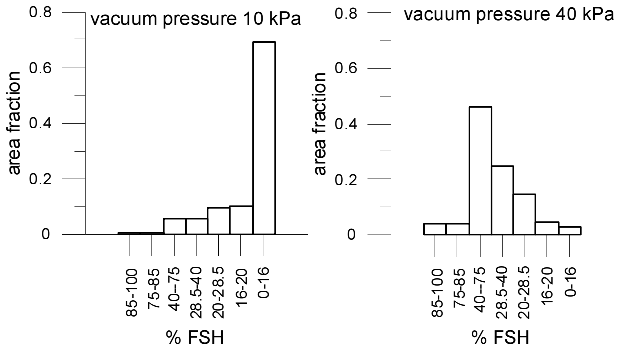


Fig. 6. Plate area fractions corresponding to considered fractions of FSH for 10 and 40 kPa vacuum pressures

Rys. 6. Stosunek pól różniących się tłumieniem w stosunku do całkowitego pola płyty dla podciśnień 10 i 40 kPa

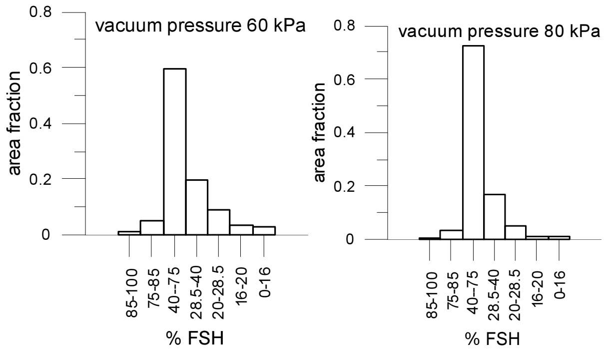


Fig. 7. Plate area fractions corresponding to considered fractions of FSH for 60 and 80 kPa vacuum pressures

Rys. 7. Stosunek pól różniących się tłumieniem w stosunku do całkowitego pola płyty dla podciśnień 60 i 80 kPa

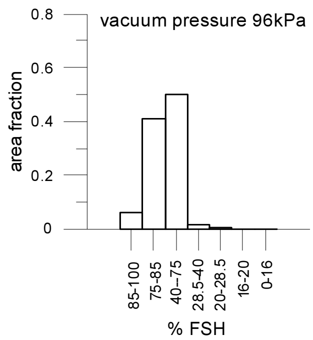


Fig. 8. Plate area fractions corresponding to considered fractions of FSH for 96 kPa vacuum pressure

Rys. 8. Stosunek pól różniących się tłumieniem w stosunku do całkowitego pola płyty dla podciśnienia 96 kPa

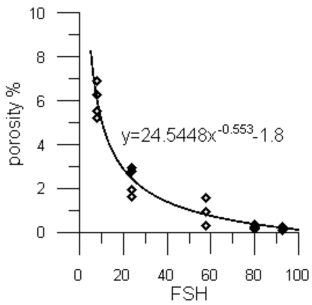


Fig. 9. Experimental relationship of porosity versus ultrasound attenuation expressed in FSH

Rys. 9. Doświadczalna zależność porowatości w funkcji tłumienia wyrażonego w FSH

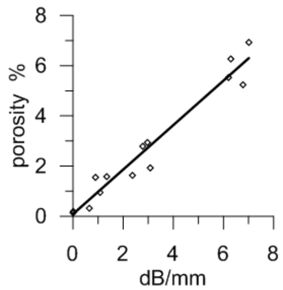


Fig. 10. Experimental relationship of porosity versus coefficient of ultrasound attenuation

Rys. 10. Doświadczalna zależność porowatości w funkcji współczynnika tłumienia

DISCUSSION OF RESULTS AND CONCLUSIONS

Upon analysis of the AU contour plots related to the plates cured under 10, 40, 60, 80 and 96kPa vacuum pressures (Figs. 3-5) and the bar plots (Figs. 6-8), and making use of the porosity vs. FSH relationship (Fig. 9) one can notice that the vacuum pressure played a crucial role in porosity reduction. An increase in vacuum resulted in a decrease in porosity, however, in none of the investigated plates were the pores distributed in a uniform manner. In all the cases, the porosity decreased towards the longer plate edges to which the reinforcement fibers were perpendicular and at which the evacuation ducts were opened. Regardless of the vacuum increase, the porosity remained relatively high in the inner regions of the plates and in the vicinity of shorter edges to which the fibers were parallel, cf. Figures 3 and 4. The clearly visible specific fringe patterns suggested the vital role played by the air ducts in laminate degasing.

The available literature provides information on the relationship between porosity and attenuation coefficient α [dB/mm] [4, 8-10]. To make a comparison of the obtained results against those from the literature, the data shown in Figure 9 were transformed to the porosity-attenuation coefficient co-ordinate system with the help of (1) [11] and then the data were approximated in the new co-ordinate system with a straight line (Fig. 10).

$$\alpha = 20\log_{10}\left(\frac{FSH}{80}\right) \tag{1}$$

Information concerning the relationship between the porosity and attenuation coefficient found in the literature was not consistent. Some authors found it non linear [10] others found it linear [7, 9] or both [4]. This contradiction could be attributed to the different ultrasound frequencies used in the tests or changes in void geometry with vacuum pressure.

The following conclusions could be drown:

- vacuum pressure played a vital role in porosity formation,
- porosity higher than 2% occurred for vacuum lower than 80 kPa,

- plate degasing remained non uniform regardless of the vacuum increase,
- air duct pronouncedly enhanced air evacuation,
- in light of the results found in the available literature, the porosity vs. attenuation coefficient relationship is not clear and needs further investigation.

Acknowledgements

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