UDK: 616.31:678:621.792
COSATI: 11-04

Filament Wound Composite Plastic Tubes: Relationship Between Winding Structures and their Hydraulic and Mechanical Properties

Jovan Radulović[1)]

A winding structure denotes the number of layers and the winding angle at which a reinforcing fiber is wound. regarding the tube longitudinal axis. Tubes with four different winding structures were produced by the filament winding technology of glass roving impregnated by a polyester resin system. Test tubes for hydraulic testing and ring specimens for mechanical investigation were produced by machining. Test tubes with four different winding structures were exposed to the influence of internal fluid hydraulic pressure. The burst pressure, radial deformation and radius displacement were determined. The ring specimens were exposed to tensile stress and their ultimate strength was determined.

It is concluded that the winding structure has the essential influence on the hydraulic and mechanical properties of filament wound composite plastic tubes.

Key words: **composite materials, polymers, filament winding, winding structure, tube, mechanical properties.**

Introduction

MATERIALS are solid or liquid substances used for the production of various articles. Due to increasingly specific and diverse requirements with regard to systems and corresponding parts, there are demands for materials which will satisfy exploitation requirements. The second half of the previous century and the first decade of the current century is a period sometimes called the composite materials epoch.

Composite materials

The term composite originally arose in engineering when two or more materials were combined in order to rectify shortcomings of particularly useful components [1, 2]

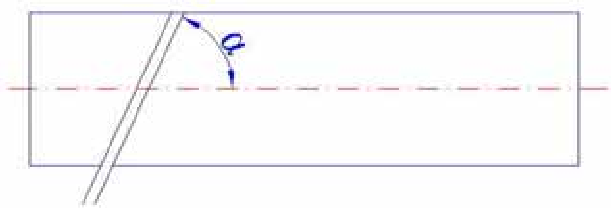
Composite materials are usually formed of two or more materials and characterized by new properties with regard to starting components. One of composite materials production technology increasingly used is the filament winding technology. Filament wound polymeric composites consist of an reinforcing agent and an impregnating agent. Reinforcing agents can be polymer-based (carbon fibres, graphite fibres, aromatic polyamide fibres (aramide), novoloid fibres, etc) and nonpolymeric (glass fibres) ones. Impregnating agents are mostly polymeric (polyester resins, epoxy resins, phenolic resins and other thermoreactive resins). It is considered that there are more than 5.000 of composite polymeric materials [3].

The filament winding technology, in brief, consists of winding fiber reinforcing agents previously impregnated by a resin impregnating system on the mandrel, curing wound structure and removing the cured product from the tool.

The essential property and the advantage of the filament winding technology over other composite materials production procedures is a fact that the reinforcing agent is placed into the direction of the load that may be expected during exploitation of a filament wound product. Owing to this unique capability, the mechanical properties of fibers in the longitudinal direction can be maximally exploited. Filament wound composite materials have a unique set of specific properties so they very often represent the only choice for numerous purposes [3,4].

Based on theoretical considerations and practical experience on the investigation and development of polymeric composite materials obtained by the filament winding technology, it is known that the characteristics of the mentioned materials depend on the reinforcing agent and the impregnating agent as well as on the technological parameters of the production process [1].

The winding structure is one of the most important parameters of the filament winding technology. It denotes the winding angles regarading the longitudinal axis of the product and the number of layers. The winding angle is shown in Scheme.1.



Scheme 1. Winding angle

This paper presents the results of the investigation of the dependence between four different winding structures and the hydraulic and mechanical properties of composite polymeric tubes obtained by the filament winding of glass fiber impregnated by a polyester resin system. The burst pressure, radial deformation and radius displacement of tubes (under the influence of internal hydraulic pressure) and the tensile strength of test rings (under the action of radial tensile stress) are determined.

[1)] Military Technical Institute (VTI), Ratka Resanovića 1, 11132 Belgrade, SERBIA

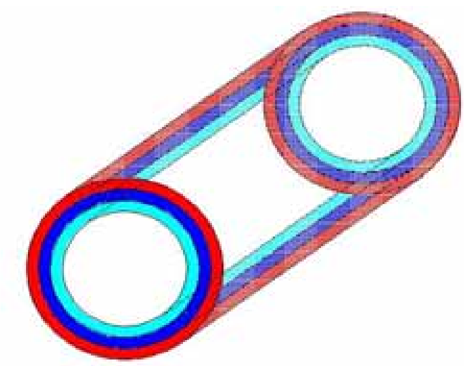
The relationship between the winding structures and the hydraulic and mechanical properties of filament wound composite polymeric tubes was defined by comparing the values of the burst pressure, the radial deformation and the radius displacement as well as the values of the radial tensile strength of tubes with four different winding structures.

Experimental part

The test tubes with four diffrenet winding structures were produced by the filament winding technology using the PLASTEX type PLA 500 machine, made by the machine manufacturer PLASTEX-MANUHRINE, France. The mentioned plastic tubes were obtained by winding a glass roving R 2117, made by the glass fibre manufacturer "ETEX", Baljevac/Ibar, impregnated by a polyester resin system DUGAPOL H 230 on a cylindrical mandrel. The used polyester resin system consists of unsaturated polyester resin DUGAPOL H 230, a hardener N and an accelerator N, made by the polyester resin manufacturer "DUGA", Serbia, with the addittion of an inhibitor TBC, produced by the chemical producer AKZO, Netherland.

The wound tubes were exposed to the cure schedule proposed by the resin system manufacturer. The cured tubes were removed from the mandrel and by the machining process only a layer of pure resin was removed from the outer surface of tubes, so that the final layer of glass fiber remained undemaged. The test tubes 400 mm long for the hydraulic testing and the rings 10 mm wide for the mechanical investigation were produced in the described manner.

The winding structure of the tube samples is shown in Scheme 2.



Scheme 2. Winding structure of the tube samples

The marks, the winding structure (from the internal towards the external surface) and the wall thickness of four groups of tube samples are presented in Table 1.

Table 1. Marks, the winding structure and the wall thickness of four tubes and ring samples

Tubes and ring samples marks	Winding structure	Wall thickness (mm)
	1 x 90o	
I	2 x 61°	1.70
	1 x 90°	
	1 x 90°	
II	2 x 45°	1.70
	1 x 90°	
	2 x 90°	
III	4 x 61°	3.45
	2 x 90°	
	2 x 90°	
IV	4 x 45°	3.45
	2 x 90°	

The hydraulic properties of the test tubes with four different winding structures were experimentally determined by a device for monotonic increasing hydraulic pressure range 200 MPa, produced by the hydraulic equipment manufacturer WALTER & BAI, Germany, along with the protection equipment and the specific tool for testing the tubes hydraulic burst pressure.

The internal hydraulic pressure was measured with a piezoelectric converter of pressure 601H range 100 MPa, manufactured by the measuring device manufacturer KISTLER, Germany.

Two one-axis strain gauges HBB 10/120 LA 11 manufactured by the strain gauges manufacturer HOTTINGER BALDWIN MESSTECHNIK, Gmbh, Germany, were glued to the outer surfaces of the test tube for hydraulic investigation using the adhesive X 60 produced by same manufacturer.

The two mentioned one-axis strain gauges were positioned in the middle of the tube length, one opposite another, transversal to the longitudinal axis of the tubes in order to registrate radial deformations. The linear displacement indicator DC-DC-246-000 produced by the measuring equipment manufacturer TRANSTEK, USA, was positioned in the middle of the tubes, between two one-axis strain gauges, in order to measure the radius displacement of the tubes during the action of internal hydraulic pressure.

A digital oscilloscope NICOLET 4094 B with additional equipment, produced by the measuring equipment manufacturer NICOLET INSTRUMENTS, USA, was used for the simultaneous detection of the internal hydraulic pressure, radial deformation and radius displacement.

The ring specimens were mounted on a tool for determining tensile properties by the split disc method according to standard ASTM D 2290 [5]. The radial tensile strength of the ring specimens was determined by the dynamometer ZWICK type 1461, produced by the testing equipment manufacturer ZWICK, Germany.

Tubes and rings experimental results and analysis

The results of the examination of the test tubes with four different winding structures, obtained by an action of internal hydraulic pressure, are presented in tables. The values of hydraulic pressure, radial deformation and radius displacement at the moment of burst of test tubes marked I, II, III and IV are presented in Tables 2-5, respectivelly. The single test values (X), arithmetic mean values $\left(\bar{X}\right)$ and standard deviations values (σ) of the mentioned characteristics are also presented in the specified tables.

Table 2. Values of hydraulic pressure, radial deformation and radius displacement at the moment of burst of the test tubes marked I

Tube samples marks	Hydraulic pressure (MPa)	Radial deformation strain gauge 1 (mm/m) x 10^{-2}	Radial deformation strain gauge 2 (mm/m) x 10^{-2}	Average values of radial deformations (mm/m) x 10^{-2}	Radius displacement (mm)
I/1	23.08	2.08	2.06	2.07	2.17
I/2	22.50	1.86	1.94	1.90	2.09
I/3	23.49	2.30	2.30	2.30	2.25
I/4	21.56	2.32	2.30	2.31	2.26
I/5	21.10	2.03	1.89	1.96	2.03
I/6	22.31	2.31	2.25	2.28	2.07
$\bar{X} \pm \sigma$	22.34±0.90	2.15±0.18	2.12±0.18	2.13±0,19	2.15±0.1

Table 3. Values of hydraulic pressure, radial deformations and radius displacement at the moment of burst of the test tubes marked II

Tube samples marks	Hydraulic pressure (MPa)	Radial deformation strain gauge 1 (mm/m) x 10^{-2}	Radial deformation strain gauge 2 (mm/m) x 10^{-2}	Average values of radial deformations (mm/m) x 10^{-2}	Radius displacement (mm)
II/1	19.04	2.07	2.06	2.065	1.85
II/2	17.83	1.89	1.82	1.86	1.62
II/3	17.25	1.70	1.69	1.6952	1.47
$\bar{X} \pm \sigma$	18.04±0.91	1.89±0.18	1.86±0.18	1.875±0.18	1.64±0.2

Table 4. Values of hydraulic pressure, radial deformations and radius displacement at the moment of burst of the test tubes marked III

Tube samples marks	Hydraulic pressure (MPa)	Radial deformation strain gauge 1 (mm/m) x 10^{-2}	Radial deformation strain gauge 2 (mm/m) x 10^{-2}	Average values of radial deformations (mm/m) x 10^{-2}	Radius displacement (mm)
III/1	50.23	4.81	4.84	4.82	4.59
III/2	48.04	4.77	4.65	4.71	3.94
$\bar{X} \pm \sigma$	49.13±1.54	4.79±0.03	4.75±0.12	4.76±0.08	4.27±0.46

Table 5. Values of hydraulic pressure, radial deformations and radius displacement at the moment of burst of the test tubes marked IV

Tube samples marks	Hydraulic pressure (MPa)	Radial deformation strain gauge 1 (mm/m) x 10^{-2}	Radial deformation strain gauge 2 (mm/m) x 10^{-2}	Average values of radial deformations (mm/m) x 10^{-2}	Radius displacement (mm)
IV /1	36.01	3.69	3.65	3.67	3.94
IV /2	41.56	4.66	4.54	4.60	4.01
IV /3	38.02	4.06	4.10	4.08	3.77
$\bar{X} \pm \sigma$	38.53±2.81	4.14±0.48	4.10±0.47	4.12±0.47	3.91±0.1

The internal hydraulic pressures versus time for the test tubes I/1, II/2, III/2 and IV/3 are presented in Fig.1-4, respectivelly.

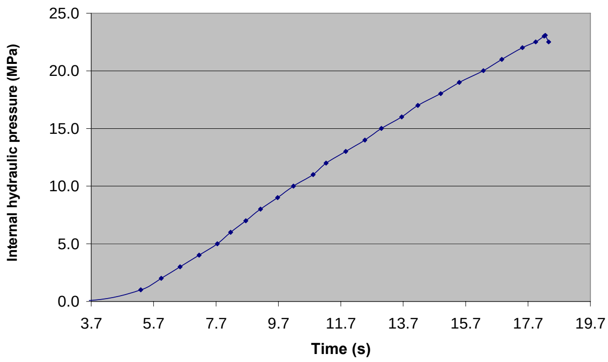


Figure 1. Internal hydraulic pressure versus time for test tube I

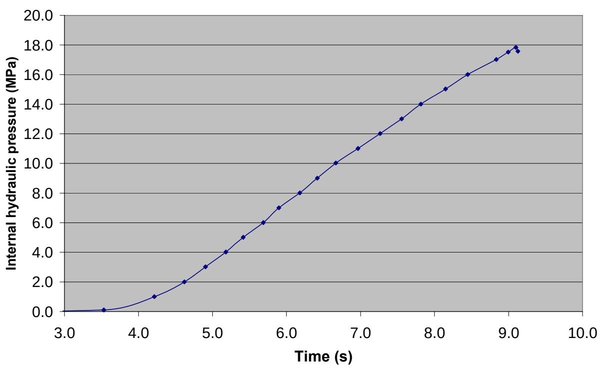


Figure 2. Internal hydraulic pressure versus time for test tube II

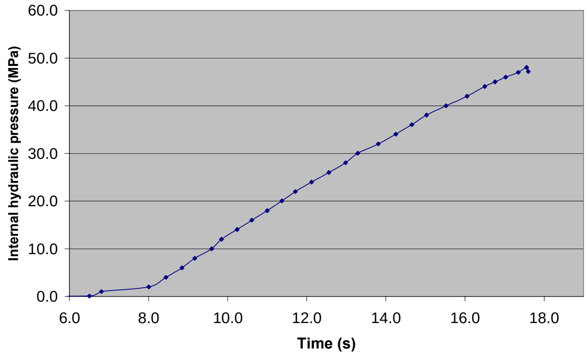


Figure 3. Internal hydraulic pressure versus time for test tube III

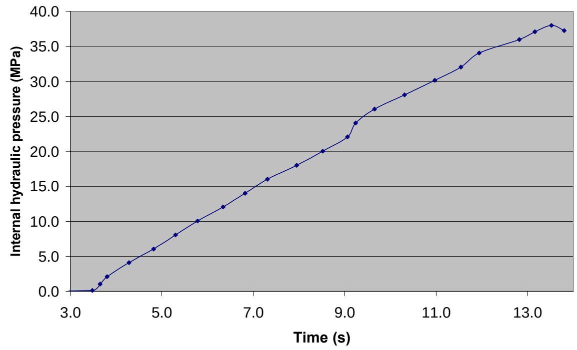


Figure 4. Internal hydraulic pressure versus time for test tube IV

At presented Figs.1-4, a monothonic increasing of the internal hydraulic pressure for test tubes I, II, III and IV, can be observed.

On the basis of all presented data, it can be stated that there are slight deviations of the single test results from the arithmetic mean values of hydraulic pressure, radial deformation and radius displacement at the burst moment of the test tubes and from the arithmetic mean values of the radial tensile strength of rings i.e. standard deviations are completely acceptable for all four group of the test tubes. Therefore, the arithmetic mean values will be used in any additional analysis.

The mark test rings and the radial tensile strength are presented in Table 6.

Table 6. Mark test tubes and rings and the radial tensile strength of rings

Rings samples marks	Radial tensile strength (MPa)	
	Single value	$\bar{X} \pm \sigma$
I	299.0; 297.4; 302.5; 291.9; 305.6; 314.4; 282.4; 293.6	298.4±9.6
II	279.1; 274.4; 271.0; 262.4; 264.1; 262.8; 261.2; 260.7	266.9±6.9
III	298.8; 293.9; 310.8; 317.1; 295.1; 300,6; 301,4; 287,0	300.6±9.5
IV	270.6; 279.6; 282.6; 276.0; 280.6; 263.9; 272.8; 258.2	273.0±8.5

On the basis of the analysis of all obtained results, presented in Tables 2, 3, 4, 5 and 6, the following can be concluded:

- structure III (samples which have two layers with the winding angle 90^{o} at the start (inside part of the specimen), four layers with the winding angle 61^{o} in the middle and two layers with the winding angle 90^{o} at the end (outer part of the specimen) and the wall thickness of 3.45 mm) has the nominally highest mean values of hydraulic burst pressure, radial deformations and radius displacement of the tubes and the radial tensile strength of rings,

- structure II (samples which have one layer with the winding angle 90° at the start (inside part of the specimen), two layers with the winding angle 45° in the middle and one layer with the winding angle 90° at the end (outer part of the specimen) and the wall thickness of 1.70 mm) has the nominally lowest mean values of hydraulic burst pressure, radial deformations and radius displacement of the tubes and the radial tensile strength of rings.

It is interesting to compare the characteristics of structure I and structure II of the tubes and rings because they have one layer with the winding angle of 90° inside and outside and the same wall thickness, but different winding structures. The structure I specimen has two layers in the middle with the winding angle 61° and the structure II specimen has two middle layers with 45° angles. It can be therefore stated:

- -the hydraulic burst pressure test tube of structure I (22.34 MPa) is bigger than the hydraulic burst pressure test tube of structure II (18.04 MPa),
- the radial deformation test tube of structure I (2.13×10^{-2} mm/m) is bigger than the radial deformation test tube of structure II (1.87×10^{-2} mm/m),
- similar relations are observed concerning the radius displacements (2.15 mm for structure I and 1.64 mm for structure II),
- the structure I rings have higher radial tensile strength (298.4 MPa) than the structure II rings (266.9 MPa).

The comparison of the hydraulic and mechanical properties of the structure III and structure IV samples, which have the same wall thickness (3.45 mm), the same number of layers (two) and the same winding angles inside and outside (90°), but which differ in the winding angle in the middle layers (61° for structure III and 45° for structure IV), shows that:

- the structures III test tubes (four middle layers with the 61° winding angle) have higher hydraulic burst pressure (49.13 MPa), radial deformations (4.76×10^{-2} mm/m) and radius displacement (4.27 mm) regarding the same characteristics of the structure IV test tubes which have four layers with the 45° angle in the middle (38.53 MPa, 4.12×10^{-2} mm/m and 3.90 mm, respectively),
- similar relations are observed concerning the radial tensile strength i.e. the structure III test rings have higher radial tensile strength (300.6 MPa) than the structure IV test rings (273.0 MPa).

The detailed analysis of the radial tensile strength calculated as a ratio of the radial tensile breaking force and the area of the initial cross section points out to an interesting phenomenon [5]. On the basis of the data presented in Table 1, it is clear that structure III represents, practically, a doubled structure I, and structure IV is, in fact, a doubled structure II. The results, presented in Table 6, point out that structures I and III with the middle layers with the 61° winding angle have, practically, the same radial tensile strength (298.4 MPa and 300.6 MPa). A similar situation is with the radial tensile strength of structure II and structure IV with four layers with the 45° angle in the middle (266.9 MPa and 273.0 MPa).

On the basis of the analysis of all obtained results, presented in Tables from 1 to 6, it can be observed that the tubes and rings of structure I and structure III with the middle layers wound under the 61° angle have higher values of the hydraulic burst pressure, radial deformations and radius displacement and radial tensile strength than the tubes and rings of structure II and structure IV with the middle layers wound under the 45° angle.

Conclusions

The analysis of all results, presented in Tables from 1 to 6 and in Figs. 1 to 4, leads to the following conclusions:

1. The winding structure i.e. the number of layers and the winding angle with regard to the longitudinal axis of the cylinder has the essential influence on the hydraulic and mechanical properties of filament wound glass fiber/polyester resin composite polymeric tubes and rings.
2. For the same number of layers, tubes and rings with the 61° winding angle have better resistance to internal hydraulic pressure and radial tensile stress than tubes and rings with the 45° winding angle.
3. The increase of the number of layers has a positive influence on the values of the hydraulic properties of tubes with the same winding angles.

References

[1] RADULOVIĆ,J.: *Characterization of Filamentwound Polymeric Composite Materials*, Scientific Tehnical Review, ISSN 1820-0206, 2008, Vol LVIII, No 1, p 66-75.

[2] KELLY,A.: *Concise Encyclopedia of Composite materials*, Pergamon Press, Oxford, 1989.

[3] ASHBY,F.M.: *Materials selection in mechanical design*, Butterworth-Heinemann, Oxford, 1999.

[4] RADULOVIĆ,J.: *Influence of Internal Cyclic Pressure on Filamentwound Composite Tube Quality*, Scientific Tehnical Review, ISSN 1820-0206, 2010, Vol LX, No 1, p 54-60.

[5] ASTM D 2290 *Apparent tensile strength of parallel reinforced plastic materials by split ring method*, ASTM Committee of Standards, Philadelphia.

Received: 09.09.2011.

Mokronamotane kompozitne plastične cevi: odnos između strukture namotavanja i hidrauličkih i mehaničkih osobina

Struktura namotavanja označava broj slojeva i uglove pod kojim se namotava vlaknasto ojačanje, u odnosu na uzdužnu osu cevi. Cevi četiri različite strukture namotavanja urađene su tehnologijom mokrog namotavanja staklenog rovinga impregnisanog sistemom poliestarske smole. Epruvete cevi za hidrauličko testiranje i uzorci prstenova za mehanička ispitivanja dobijeni su mašinskom obradom mokronamotanih cevi. Epruvete cevi četiri različite strukture namotavanja izložene su dejstvu unutrašnjeg hidrauličkog pritiska fluida i određene su vrednosti pritiska prskanja, radijalnih deformacija i promene poluprečnika. Uzorci prstenova su ispitani pod dejstvom zateznog opterećenja i određena je prekidna čvrstoća.

Zaključeno je da struktura ima bitan uticaj na hidrauličke i mehaničke karakteristike mokronamotanih kompozitnih plastičnih cevi.

Ključne reči: **kompozitni materijali, polimerni materijali, mokro namotavanje, struktura namotavanja, cev, mehaničke osobine.**

Мокронаматываные композитные пластиковые трубы: связи между структурой наматывания и гидравлических и механических свойств

Структура наматывания означает число слоев обмотки и углы, под которыми намотаны армирующие волокна по отношению к продольной осе трубы. Трубы из четырёх различных структур наматывания производятся по технологии мокрого наматывания стеклянного ровинга, пропитанного системой полиэстерной смолы. Трубы для гидравлических испытаний труб и образцы колец для механических испытаний были получены путём машинной обработки мокронаматываных труб. Трубы четырёх различных структур наматывания подвергаются воздействию внутреннего гидравлического давления рабочей жидкости и определены значения давления взрыва, радиальных деформаций и изменения радиуса. Образцы колец были протестированы под воздействием растягивающих напряжений и определена прочность на разрыв. Здесь сделан вывод, что структура оказывает существенное влияние на гидравлические и механические свойства мокронаматываных композитных пластиковых труб.

Ключевые слова: **композитные материалы, полимерные материалы, мокрое наматывание, структура наматывания, труба, механические свойства.**

Les tuyaux plastiques composites à filament enroulé: les rapports entre la structure de filament et des propriétés hydrauliques mécaniques

La structure du filament indique le nombre des couches et les angles sous lesquelles est filé le renforcement de fibre par rapport à l'axe axiale du tuyau. Les tuyaux avec quatre différentes structures de filament ont été produits par la technologie du filament enroulé de roving en verre imprégné par le système de résine polyester. Les éprouvettes des tuyaux d'essai hydraulique et les échantillons des anneaux pour les tests mécaniques ont été produits par le traitement mécanique des tuyaux à filament enroulé. Les éprouvettes des tuyaux de quatre différentes structures de filament sont exposées à l'action de la pression hydraulique interne des fluides et on a déterminé les valeurs de la pression d'éclatement, les déformations radiales et le changement du rayon. Les échantillons des anneaux ont été testés à l'action de la charge de traction et on a déterminé la résistance à la rupture. On a conclu que la structure influence essentiellement sur les caractéristiques hydrauliques et mécaniques chez les tuyaux plastiques composites à filament enroulé.

Mots clés: **matériaux composites, matériaux polymériques, filament enroulé, structure du filament, tuyau, caractéristiques mécaniques.**