doi: 10.5937/str2600004G

Structural and Mechanical Properties of Hybrid Carbon and Glass Fiber-Reinforced Thin-Walled Composite Tubes: Filament Winding Angle Influence

Jelena D. Gržetić [1)]
Jela Galović [1)]
Ivana Vinčić [2)]
Saša Brzić [1)]
Tihomir Kovačević [1)]

This paper presents the development, structural and mechanical characterization of composite thin-walled tubes (CF/GF/UPe) based on a polyester resin matrix, reinforced with carbon (CF) and glass fibers (GF). The tubes were fabricated using wet filament winding technology, which offers precise control over fiber orientation. The manufacturing process involved two distinct winding patterns: radial and helicoidal, to assess their effects on the mechanical performance of the tubes. Detailed experiments were conducted to evaluate the influence of the winding angle (radial vs. helical) on the internal hydrostatic pressure. It was observed that the helicoidal winding pattern, particularly at a winding angle of 70°, significantly enhanced the response of the CF/GF/UPe tubes on internal hydrostatic pressure. The findings provide valuable insights into the design and fabrication of composite tubes for applications requiring high strength-to-weight ratios, such as in automotive, aerospace, and structural engineering fields. The research offers a comprehensive understanding of the relationship between filament winding parameters especially winding angle, and the mechanical performance (Barcol hardness and response of the material to internal hydrostatic pressure) of novel composite thin-walled tubes, providing a basis for future optimization in the production of fiber-reinforced composite tubes.

Key words: **polyester resin; helicoidal, radial; fiber-based composites.**

Introduction

NOWADAYS, society has made a remarkable progress in the use of composite materials in many industrial areas, e.g. construction, automotive, aerospace and military industry [1], [2]. Composite materials for military application such as ballistic protection or elements in rocket motor constructions are mostly based on fibers of high toughness and tensile strength, like aramid, carbon or glass fabrics, impregnated with a thermoplastic or thermosetting polymer, or their combination [3], [4]. Thin-walled lightweight composites such as carbon and/or glass fiber reinforced polymers (CFRP or GFRP, respectively), have been increasingly used in rocket motors or launch system due to their high corrosion resistance and good mechanical properties [5]–[7].

Depending on the composite system, i.e. the selected combination of polymer matrix and reinforcement in conjunction with the designed geometry and application of the final product, different processing technologies have been developed to achieve optimal mechanical performances in the most efficient way. Filament winding is a commonly used technology for the production of composites, which includes wetting the fibers with a polymer matrix (optional in wet filament winding) and laying the fibers in prescribed patterns [8]–[10]. There are three types of winding patterns in filament winding [11] (helical, hoop/radial and polar patterns - Figure 1.1), which in combination with the winding angle significantly affect the structural and mechanical performances of the final composites [5]. In general, a higher winding angle is for higher circumferential strength, while a lower angle is for higher longitudinal strength of the final product [10].

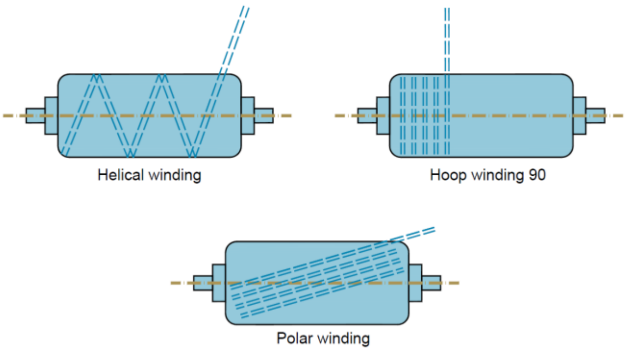


Figure 1.1. Filament winding patterns

There are several researches that study the influence of filament winding parameters on the mechanical properties of composite cylindrical structures. For instance, Ma et al. studied the mechanical properties of filament-wound carbon fiber-reinforced polymer tubes under quasistatic radial and axial compression tests. The authors investigated the influence of filament winding angle (±45°, ±60°, and ±75°)

1) Military Technical Institute, Ratka Resanovića 1, 11030 Belgrade, Serbia
2) HK Krušik a.d., Vladike Nikolaja 59, 14000 Valjevo, Serbia
Correspondence to: Jelena D. Gržetić, e-mail: jrusmirovic@tmf.bg.ac.rs

on the axial and radial crushing behavior [5]. They found that the peak crushing load increased with increasing winding angle under radial compression, while the maximum energy absorption and specific energy absorption were 12.51 J and 1.32 kJ/kg, respectively, at a winding angle of ±75°, which was improved by 1.37 times compared to a winding angle of ±45° [5]. Moreover, Krishnan et al. [12] investigated the influence of winding angle in glass/epoxy composite pipes subjected to multiaxial cyclic pressure loadings. They evaluated a strong dependence on the stress-winding angle ratio. The $[\pm45]_4$ angle tends to be axially dominant, while $[\pm63]_4$ behaves better under high hoop-dominant loading [12].

This paper deals with the effect of winding angle/pattern (helical pattern with an angle ±70° and hoop (radial) with an angle of 90°) on novel hybrid composite thin-walled tubes based on polyester (CF/GF/UPe) reinforced with carbon and glass fibers (CF and GF, respectively). In general, structural composition of the developed hybrid composite thin-walled tubes, which is composed of combination of carbon fiber fabric of two areal densities (480 $g\cdot m^{-2}$ and 200 $g\cdot m^{-2}$) and carbon/glass fiber rovings, makes them novel considering used materials and manufacturing technique. According to our best knowledge, reinforcing fabrics are not applied for production thin-walled tubes using wet filament winding technique due to complexity of their integration in final product. In the presented research, we developed not only the hybrid composite thin-walled tubes but also a technique for using carbon fiber and fiberglass fabrics in wet filament winding process. Furthermore, geometric dimensions and mechanical properties, e.g. Barcol hardness and response of the material to internal hydraulic pressure, were experimentally investigated in order to establish the potential of application of such material in rocket motor constructions.

Experimental part

2.1. Materials

Two types of fabrics were used for the production of composite: carbon fiber fabrics (480 $g\cdot m^{-2}$ Plain 1/1 and 200 $g\cdot m^{-2}$ Twill 2/2, Multitex – composites, Bulgaria). The fabrics were tensioned with carbon fiber roving (Tenax HTS40 F13, 800 tex, R&D Faserverbundwerkstoffe GmbH, Germany) and fiberglass roving, (E Glass Direct Roving/600 tex – Jushi Group Co. Ltd). A pre-filled, halogen-free unsaturated polyester resin (UPe), Dion® FR 7721-00, (Reichhold, USA), containing alumina tri-hydrate as a fire-retardant was used as a polymer matrix for composite preparation. The 50% solution of the methyl ethyl ketone peroxide in toluene (MEKP, Sigma Aldrich, Germany) was used as the curing agent for the UPe resin.

2.2. Manufacturing of CF/GF/UPe composite thin-walled tubes

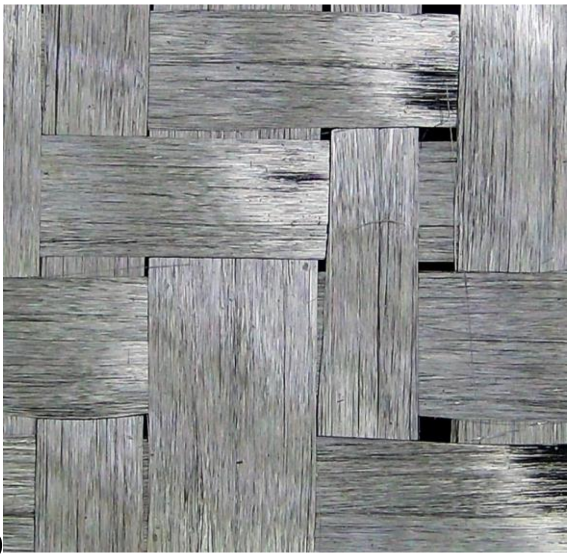
Composite laminates were prepared using a wet filament winding machine (Forplex Plasterex, France) [6], equipped with Winding Expert software (Mikrosam, Prilep, North Macedonia). A cylindrical rotating mandrel (2220 mm×φ119 mm) was used to produce thin-walled tubes (wall thickness 2.05 – 2.23 mm). The composite structure was complex and contained 200 $g\cdot m^{-2}$ carbon fiber fabric tightened with carbon fiber roving (radial winding – angle 90°) in the first zone (from the inner diameter of the composite tube), then 480 $g\cdot m^{-2}$ carbon fiber fabric tightened with fiberglass roving (radial winding – angle 90°) in the second zone (continues to zone I). Finally, the third zone was different for CF/GF/UPe composite I and II and composed of 200 $g\cdot m^{-2}$ carbon fiber fabric tightened with fiberglass roving (radial winding – angle 90° (CF/GF/UPe composite I) and helical winding – angle 70° (CF/GF/UPe composite II). The fabrics were impregnated with pre-accelerated UPe resin after being placed on a mandrel, while CF/GF rovings run through the resin bath and were wound over the fabric. Moreover, the filament winding parameters were different (number of layers and cycles) depending on the winding angle. The software settings for the winding parameters are summarized in Table 2.1. The composites were cured at 80 °C for 3 h.

Table 2.1. Filament winding parameters for the third zone

	CF/GF/UPe composite I	CF/GF/UPe composite II
Velocity ($m\cdot min^{-1}$)	22.4	22.4
Roving tape width (mm)	12.0	12.0
Winding angle (°)	90	70
Intertwining	/	1/1
Layer number	5	1
Cycle number	/	11

2.3. Characterization methods

The reinforcements used (Figure 2.1) were fully characterized according to the standard methods: SRPS EN ISO 1889:2013 (linear density), JUS F.S2.016/1986 (fabric surface area and thread density), SRPS EN ISO 5084: 2013 (fabric thickness), SRPS EN ISO 3341:2000 (mechanical characterization of CF/GF rovings). The mechanical characterization of CF/GF roving was performed using an Instron 1122 machine equipped with round clamps for a specimen length of 250 mm and flat clamps for a specimen of length of 500 mm at a testing speed of 200 $mm\cdot min^{-1}$. The following properties were determined: breaking force (F in N), breaking strength (σ in $N\cdot tex^{-1}$) and elongation at break (ε in %). Tensile strength of the CF/GF fabrics was tested on 200 mm x 50 mm specimens according to the SRPS EN ISO 13934-1: 2015 standard using an Instron 1122 tensile testing machine equipped with flat clamps at a speed of 100 mm $\cdot min^{-1}$.

a) 

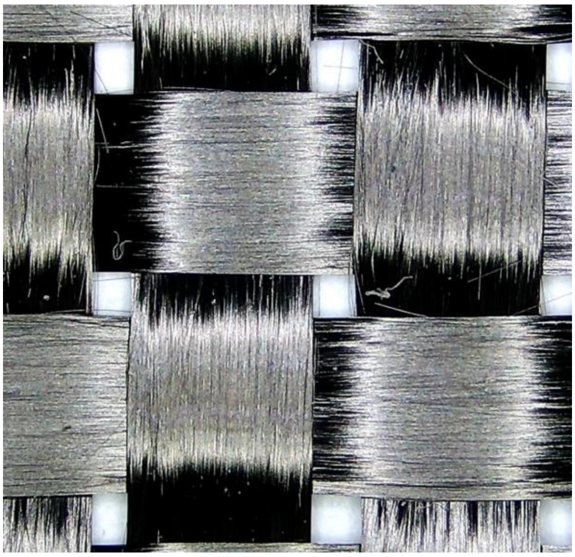
b) 

Figure 2.1. Samples of s) carbon 200 g/m^2 and b) carbon 480 g·m^{-2} fabric

Microstructural analysis of the cross-section of the thin-walled composite tubes was performed using SMTV Visor Inspection System (Michael Bruch, Germany).

Following mechanical characteristics of CF/GF/UPe thin-walled composite tubes were determined: hydrostatic pressure resistance (Figure 2.2 – test set-up) and Barcol hardness using HPE II BARCOL - digital Barcol durometer, Bareiss.

Hydrostatic pressure test was performed by placing a composite tube between two metal flanges that ensured the sealing of the tubes (Figure 2.2a). The water was introduced under pressure through the left flange. Comparators were placed on the tubes to detect changes in the diameter caused by the increase of hydrostatic pressure (Figure 2.2b). The pressure was measured using a manometer. Pressure at which the first release/cracking of the material occurred as well as pressure at which bursting occurred were recorded. The recorded pressure values were those at which the formation of cracks and water leakage from the pipe were visually observed.

a)

b)

Figure 2.2. Hydrostatic pressure resistance test set-up

Results and discussion

3.1. Reinforcements characterization

Physical and mechanical properties of glass and carbon-based reinforcement are of a great importance for the mechanical properties of the final composite materials [6], [13], [14]. Moderate linear density (595 and 814 tex for both rovings, E Glass Direct Roving and Tenax HTS40 F13, respectively) causes better mechanical properties due to the uniform surface-area-to-volume ratio that provides better interaction between the fibers and the resin matrix and consequently higher tensile strength and flexural properties. Carbon fibers show higher values of breaking force and strength compared to the fiberglass roving (Table 3.1). The carbon fibers are specific for they retain good mechanical characteristics even at higher temperatures, which makes them suitable for military and aerospace engineering. The results of determination of the physical and mechanical properties of the fiberglass and carbon rovings are shown in Table 3.2.

Table 3.1 Physical and mechanical properties of fiberglass and carbon roving

Material properties	E Glass Direct Roving/600 tex	Tenax HTS40 F13/800 tex
linear density (tex)	595	814
breaking force (N)	166* (173**)	634* (682**)
breaking strength (N/tex)	0.30* (0.30**)	0.78* (0.84**)
elongation at break (%)	3.9* (1.4**)	3.5* (1.1**)

Values determined *using round clamps for a specimen length of 250 mm, and **using flat clamps for a specimen of length of 500 mm

Woven carbon fabrics with moderate surface area (Table 3.2) were used in CF/GF/UPe thin-walled composite structures. In general, woven fabrics provide more balanced mechanical properties in multiple directions. The established characteristics make the selected carbon fabrics suitable for the manufacturing of thin-walled complex-structure/shape composites such as novel CF/GF/UPe tubes.

Table 3.2. Physical and mechanical properties of carbon fabrics

Material properties	Carbon fabric (480 g·m^{-2} Plain 1/1)	Carbon fabric (200 g·m^{-2} Twill 2/2)
surface area (g m^{-2})	446	192
thread density (thread number·cm^{-1})	3.2	4.9
thickness (mm)	0.75	0.4
breaking force (N/5cm)	4242* (3930**)	2260* (1269**)
elongation at break (%)	2.5* (3.0**)	2.0* (1.3**)

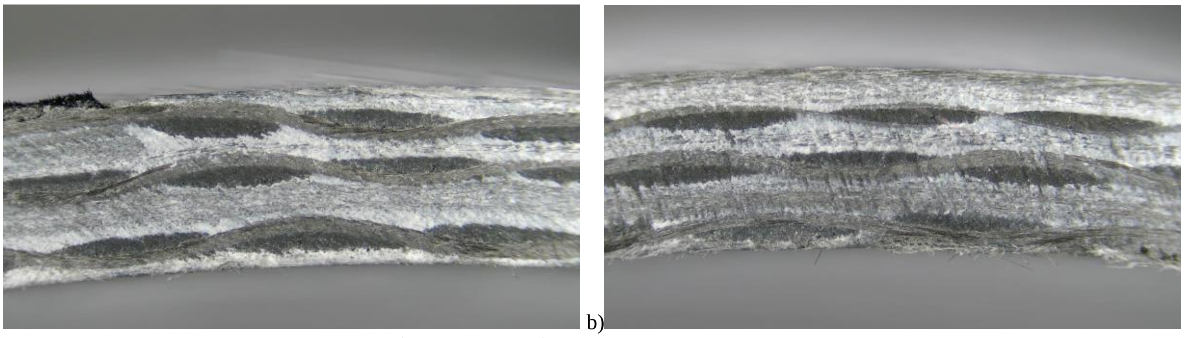
*basic, and **weft weaving

3.3. Structural characterization of CF/GF/UPe thin-walled composite tubes

The geometric dimension of CF/GF/UPe composites i.e., thickness (t), outer diameter-thickness ratio (do/t), length-outer diameter ratio (l/do), inner diameter-outer diameter (di/do) are summarized in Table 3.3. Geometric dimensions influence the mechanical properties of the thin-walled composite tubes and their analysis is of importance for determination of functional requirements and tolerances in manufacturing process [15]. We confirmed that the change in winding angle configuration from radial to helical leads to an extra tensioning which also contributes to differences in wall thicknesses of the CF/GF/UPe composite I and CF/GF/UPe composite II tubes [16]. Microstructural analysis of the cross-section of the thin-walled composite tubes was used for a more detailed observation on the influence of the filament winding pattern on the reinforcing layers compactness [6] and it is presented in Figure 3.1.

Table 3.3. Geometric dimension analysis

Sample	l, mm	t, mm	di	do	do/t	l/do	di/do
CF/GF/UPe composite I	2195	2.23	119.0	121.23	54.36	18.11	0.97
CF/GF/UPe composite II	2195	2.05	119.0	121.05	59.05	18.13	0.98



a) b)

Figure 3.1. Microstructural analysis of cross-section of the a) CF/GF/UPe composite I and b) CF/GF/UPe composite II

In Figure 3.1. it can be observed that the compact composite structure without any voids, as well as good CF and GF impregnation, was obtained using both radial and helical winding patterns. However, helical winding provides higher thickness of the glass fiber layer in the third zone (helical circumferential reinforcement layer) in the CF/GF/UPe composite II. On the other hand, lower total thickness of the first and second zone of the CF/GF/UPe composite II indicate that higher degree of the tensile force was applied using helical winding pattern compared to the radial. The microstructural analysis confirmed the results obtained by geometric analysis where the 2.05 mm of wall thickness was determined for CF/GF/UPe composite II.

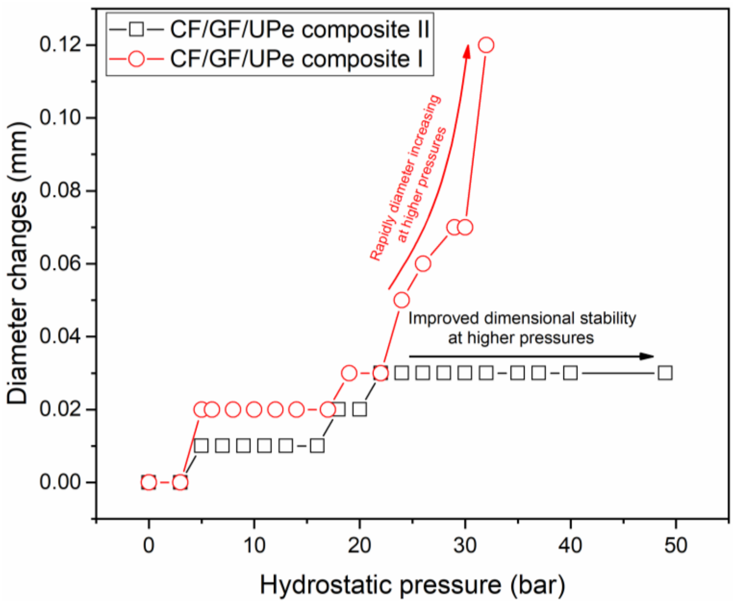
3.4. Hydrostatic pressure resistance of CF/GF/UPe thin-walled composite tubes

Hydrostatic pressure resistance tests show that the winding pattern of the circumferential reinforcement layer of a composite tube affects its overall strength (Table 3.4). Changing the winding pattern of the third zone of CF/GF/UPe composite tube from hoop (winding angle 90°) to helical (winding angle 70°) increases the resistance of the tube to hydrostatic pressure [12]. The first low intensity spraying was observed at 49.0 bar for CF/GF/UPe composite II (helical circumferential reinforcement layer), while the same phenomenon for CF/GF/UPe composite I was observed at ≈2.9 times lower pressure. Moreover, there was no obvious structural fracture of CF/GF/UPe composite II. Better dimensional stability at higher pressures was observed for CF/GF/UPe composite II, while a rapid diameter increase at pressures higher than 20 bar was observed for CF/GF/UPe composite I (Figure 3.2b). The obtained results can be explained with a higher degree of the tensile force that was applied using helical winding pattern compared to the radial causing more efficient tightening and consequently higher thickness of the helical circumferential reinforcement layer in the CF/GF/UPe composite II.

Table 3.4. Hydrostatic pressure test data

Sample	Low intensity spraying pressure (bar)	High intensity spraying pressure (bar)	Burst pressure (bar)	Diameter changes Comparator I	Diameter changes Comparator II
CF/GF/UPe composite I	17.0	32.0	44.5	0.02 mm (at 17 bars)/0.12 mm (at 32 bar)	0.08 mm (at 17 bars)/0.13 mm mm (at 32 bar)
CF/GF/UPe composite II	49.0	55.8	/	0.03 mm (at 49 bar)	0.04 mm (at 49 bar)

a)



b)

Figure 3.2. a) Leakage failure observed during hydrostatic pressure test b) radial deformations (diameter changes) versus internal hydrostatic pressure

3.5. Barcol hardness

Barcol hardness was determined for the thin-walled CF/GF/UPe composite tubes. 100 mm long rings were cut out from the composite tubes and tested (Figure 3.3). The Barcol hardness was determined in three different positions on each test sample. The measurement was performed by placing a Barcol hardness tester on the sample, which was mounted on a four points support, and applying a force of 10 kg (Figure 3.3). High Barcol hardness are obtained for CF/GF/UPe composite I and II (65.1±0.77 and 60.47±2.83). The obtained results signify a well-cured UPe matrix leading to satisfied required mechanical performances. Lower standard deviation for CF/GF/UPe composite I indicates better uniformity of the circumferential reinforcement layer which is evident since there is no obvious overlapping of the fiberglass roving strip in radial filament winding.

Figure 3.3. Barcol hardness test set-up.

Conclusion

The aim of this paper is to develop composite thin-walled tubes based on UPe and carbon fabric of two areal densities (480 $g\cdot m^{-2}$ and 200 $g\cdot m^{-2}$) and carbon and glass rovings for extreme operational conditions such as high pressures and temperature which occurs in rocket motor. The wet filament winding technique was applied in tubes manufacturing process. Two types of composite tubes (CF/GF/UPe composite I and II) are designed in three continual zones from the inner diameter of the composite tube to the external, where the latter one differs in the winding method of the glass roving. The third zone within CF/GF/UPe composite I and II is wound radially and helically, respectively. Dimensional and microstructural analysis confirm compact composite structure without any voids and good CF and GF impregnation with UPe resin. To examine the mechanical integrity of the tubes, they are subjected to a hydrostatic pressure resistance test where CF/GF/UPe composite II shows significantly better durability compared to CF/GF/UPe composite I (≈2.9 higher pressure). Contrary to this, the Barcol hardness is slightly higher for CF/GF/UPe composite I due to the better packing of the roving layers wound in radially rather than helically. The research provides valuable insights into the design and fabrication of thin-walled composite tubes especially considering the combination of carbon fiber fabric of two areal densities (480 $g\cdot m^{-2}$ and 200 $g\cdot m^{-2}$) and carbon/glass fiber rovings in one composite structure.

Acknowledgement

The authors are grateful to the Ministry of Science, Technological Development and Innovation of the Republic of Serbia for the financial support provided, as a part of the projects: Contract No. 451-03-137/2025-03/200325 and 451-03-34/2026-03/200325.

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Received: 17.12.2025.
Accepted: 02.02.2026.

Strukturna i mehanička svojstva hibridnih tankozidnih kompozitnih cevi ojačanih ugljeničnim i staklenim vlaknima: Ispitivanje uticaja ugla namotavanja

U ovom radu opisana je tehnologija izrade, razvoj, structurna i mehanička karakterizacija kompozitnih tankozidnih cevi (CF/GF/UPe) na bazi poliestarske smole ojačane ugljeničnim (CF) i staklenim vlaknima (GF). Tankozidne cevi su proizvedene tehnologijom mokrog namotavanja primenom dva različita načina namotavanja: radijalni ili helikoidni u cilju određivanja uticaja načina namotavanja na mehanička svojstva cevi. Detaljna analiza je sprovedena da bi se ispitao uticj načina namotavanja (helikoidni/radijalni) na otpornost cevi na unutrašnji hidrostatički pritisak. Potvrđeno je da helikoidni obrasac namotavanja (ugao namotavanja 70°) značajno povećava otpotnost CF/GF/UPe cevi na unutrašnji hidrostatiči pritisak. Rezultati istraživanja daju značajan doprinos u razvoju i izradi tankozitnih kompozitnih cevi za primenu u konstrukcijama koje zahtevaju obezbeđivanje dobrih mehaničkih karakteristika i otpornosti na pritisak i malu masu, kao što su konstrukcije u automobilskoj industriji, razvoju raketnih motora i građevinarstvo. Takođe, ostvaren je značajan doprinos u definisanju odnosa parametara u procesu mokrog namotavanja, prvenstveno ugao namotavanja i mehaničkih svojstava (tvrdoća po Barkolu i otpornost na hidrostatički pritisak) hibridnih tankozidnih kompozitnih cevi, čime je stvorena baza za optimizaciju postupka izrade tankozidnih kompozitnih cevi ojačanih staklenim i ugljeničnim vlaknima.

Ključne reči: **poliestarska smola; helikoidni način namotavanja; radijalni način namotavanja; kompoziti ojačani vlaknima.**