Thermal Stability and Hoop Tensile Properties of Glass Fiber Composite Pipes

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***Abstract*—Aim of this work is to present the thermal properties and mechanical behaviour of glass fibre/epoxy resin filament wound tubular structures winded with different winding angles. Conducted thermal analysis have demonstrated thermal stability of used epoxy resin system even at temperatures higher than 130ºC and small percent of weight loss until temperature of 350ºC. With help of split-disc test hoop tensile strength of manufactured composite samples was investigated. Received results have confirmed the expectations that use of higher winding angle in filament winding technology lead to better mechanical properties of composite tubular structures subjected under internal pressure. Also, fibre-matrix deboning was determined as failure mechanisms by all samples. SEM images have confirmed good merger between reinforcement and the matrix.**

Keywords: thermal analysis, mechanical behaviour, filament wound composite

I. INTRODUCTION

Fiber reinforced polymer composites are considered as a substitute for infrastructure components or systems that are constructed of traditional civil engineering materials, namely metal, due to their properties such as: lightweight, corrosive resistant, high specific strength and specific stiffness, ease of construction and given possibility of their design to satisfy performance requirements. Due to the limited understanding of the behavior of these structures under internal pressure their usage has been limited. Therefore, glass fiber reinforced (GRP) pipes are designed either for gravitational or pressurized transportation of fluids and usually they are tested under ring deflection or internal pressure conditions [1-3].The most important requirement of a composite GRP is that it must provide considerable strength and reliability to provide safe operation. Fiber reinforcements also play a decisive role in the development of high pressure GRP pipes. Most commonly, E-glass has been the preferred choice of reinforcing fiber used. These reinforcing composites are crucial for increase of corrosion resistance and also contribute to lifetime expansion of the pipe. GRP can be used for a variety of applications, above and under the ground such as in firewater systems, cooling water systems, drinking water systems, waste water systems, sewage systems and gas systems. GRP pipes can be used as a practical alternative to metal pipes in applications where corrosion, weight, environment and various other factors limit the use of metal pipes [4-8]. The structures, produced by the filament winding (FW) technique are becoming more complicated in terms of geometry and loading. This factor necessitates the usage of computational methods in the analysis of filament wound structures.

In the study of Erdiller [4], the response of filament wound composite tubes under various loading conditions was investigated by the finite element method. Hoop tensile strength and longitudinal tensile strengths and modulus were considered during the study and the development of a computer program was performed for design and analysis purposes.

The purpose of this study is to analyze the thermal degradation of filament wound glass fiber/epoxy resin tubular samples manufactured with different winding designs and to determine sample's mechanical behavior with help of split disk test. More specifically, this experimental investigation will determine the maximal hoop tensile modules of manufactured composite samples and the influence of winding angle on mechanical properties in composite samples. Also, scanning electron (SEM) analysis will show the impregnation quality of glass fiber reinforcement in the epoxy matrix.

II. EXPERIMENTAL

For manufacture of filament wound tubular samples were used four bobbins of glass fiber roving 185P 1200tex from Owens Corning as reinforcement and Araldite LY 1135/Aradur 917/Accelerator 960-1, an epoxy resin system with anhydride hardener from Huntsman as matrix. Resin viscosity at 22ºC was 1158mPas measured with portable laboratory viscometer Viscolite 700 from Hydramotion. For the filament winding process was used laboratory filament winding machine FAW FB 6/1 with six axes and electrical fiber creel from Mikrosam AD. The creel applied constant fiber tension of 64N during samples production. Impregnation process of reinforcement was performed in roller type impregnation bath, where the amount of impregnated matrix was controlled with knife. Winding process was conduct on cylindrical iron mandrel with pins on both sides in order smaller winding angle (±10º) to be easily applied. During winding process, winding speed was variable. After winding, samples were cured with help of industrial heater at 100ºC for 6 hours.

Factorial design of experiment (DOE) with 2^2 permutations was used in the production of composite tubular samples. Levels of used control parameters, winding speed and winding angle are presented in Table 1, whereas Table 2 represents manufacturing parameters of each sample. DOE was used due to it superiority to the traditional one-variable-at a time method, which fails to consider possible interaction between filament winding factors.

TABLE I. LEVEL OF USED CONTROL PARAMETERS

Symbol	Winding parameter	Parameter level	
		1	*2*
A (x_1)	Winding angle (º)	±90	±10
V (x_2)	Winding speed (m/min)	21	5.25

TABLE II. DESIGN OF EXPERIMENT (2^2) FOR COMPOSITE TUBULAR SAMPLES

Sample Nº	X_1 (º)	X_2 (m/min)	Fiber tension (N)	Winding angle (º)	Winding speed (m/min)
1	A_1	V_1	64	±90	21
2	A_2	V_1	64	±10	21
3	A_1	V_2	64	±90	5.25
4	A_2	V_2	64	±10	5.25

Thermogravimetric analysis (TGA) of uncured epoxy resin and the thermal stability of filament wound samples were determined with help of TGA instrument from Mettler Toledo Star® System in atmosphere of argon with flow of 50ml/min. Each composite sample was heated from 25°C to 1000°C at heating rate of 20K/min.

Hoop tensile modulus of manufactured filament wound samples was determined with help of split disc test according to ASTM D2290 [9-10]. From each sample were made three test rings with full-diameter, full-wall thickness and two reduced areas located 180º apart. Each test ring was tested on split disc fixture specially designed to fix on universal testing machine Zwick/Roell Z400 with maximum stress of 400kN and loading speed of 5-10m/min (Fig. 1). All ring samples were tested until failure.

a) Prepaired composite test ring b) split disc fixture

Fig. 1. Prepaired composite test ring and split disc fixture.

Scanning electron microscopy (SEM) analyses were conducted on TESCAN VEGA3 instrument to observe the impregnation quality of reinforcements. Also, the interface between fiber and resin, fibers orientation and mechanism of failure were analyzed.

III. RESOULTS AND DISSCUSION

A. *Thermogravimetric analysis (TGA)*

Performed thermal analysis of an uncured epoxy resin system and composite samples winded with different winding parameters has given the weight loss of the matrix as a function of temperature. Thermal analysis of uncured epoxy resin was conducted as a reference to thermal analysis of composite tubular samples. Received plot of uncured epoxy resin in temperature range from 25ºC to 600ºC is given in Fig. 2.

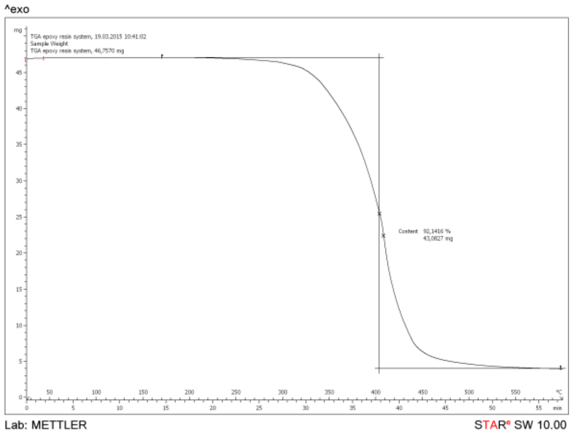


Fig. 2. TGA diagram of uncured epoxy resin Araldite LY 1135/Aradur 917/Accelerator 960-1.

With help of ASTM E 1131-03 [11] percent of highly and medium volatile matter in uncured epoxy resin was calculated. As seen from Fig. 2 uncured epoxy resin system start to lose weight at 170ºC. Until 200ºC uncured epoxy system had lost moisture, residual solvents or other low molecular weight compounds of around 0.5%. Somewhere around 350ºC more significant weight loss had started of about 10% and until 450ºC this sample had lost almost 86% of its weight. At temperature range between 450-500ºC uncured resin samples has lost 92%, where degradation of resin material with higher molecular weight formed during curing had occurred. After this temperature range, the weight loss continues to decrease with a slow degradation rate. It should be noted that at temperature of 600ºC the uncured epoxy resin system exhibit residual weight of 7.8%.

As it can be observed from Fig. 3, thermal degradation of all composites indicates weight loss process in two stages. The first stage, occurring in the temperature range from 150°C to 600°C is correlated to the degradation of the epoxy resin and for all composites is about 20%. These data are in accordance with the finds for the thermal stability of the epoxy resin. The biggest percent of degradation, around 20% has been calculated for samples winded with winding angle ±10º, sample Nº 2 and sample Nº 4. These samples also have displayed the biggest percent of mass change in the second stage of degradation, from 600ºC to 1000ºC. Since the degradation process occurs in two steps, it can be explained by the degradation phenomena associated with the different composite components.

TABLE III. THERMAL STABILITY OF FILAMENT WOUND COMPOSITE SAMPLES

Temperature range °C	Mass change (%)			
	Nº 1	*Nº 2*	*Nº 3*	*Nº 4*
150-600	16.56	20.24	15.61	20.43
600-1000	0.82	1.04	0.64	1.14

According to the received results given in Table 3, samples winded with winding angle ±90° have performed smaller mass change in comparison to samples winded with winding angle ±10°, which has been in correlation with results presented in Fig. 3.

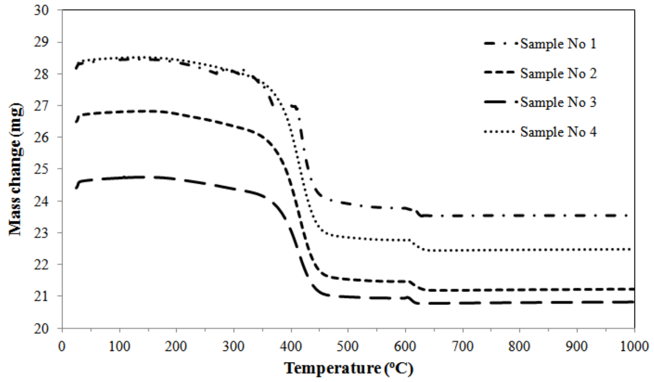


Fig. 3. Thermogravimetric analysis of manufactured composite samples.

Percent of medium volatile matter (MVM) for uncured epoxy resin and composite samples is calculated for four temperature ranges according to (1). Received results are given in Table 4.

$$MVM = \frac{m_1 - m_2}{W} \times 100\% \qquad (1)$$

In (1) m_1 and m_2 are specimen masses in mg measured at temperature T_1 and T_2, respectively. W is the original specimen mass also in mg.

TABLE IV. MEDIUM VOLATILE MATTER IN INVESTIGATED SAMPLES ACCORDING TO [11]

Samples	**Mass change (%)**			
	30 -200	***200 - 350***	***350 - 450***	***450 - 600***
Uncured epoxy resin	0.239	10.87	76.34	2.64
Nº 1	0.096	2.48	13.10	0.80
Nº 2	0.202	2.76	15.97	1.16
Nº 3	0.333	2.19	12.42	0.70
Nº 4	0.220	2.57	16.29	1.28

According to received results all composite samples produce the highest percent of MVM in temperature range from 350°C to 450°C, whereas the smallest percent of medium volatile matter is seen in temperature range from 30°C to 200°C.

Furthermore, from TGA diagrams can be noticed that winding angle and winding speed show an influence on constituent's ratio in final composite. With help of ASTM D 3171-03 [12] it was noted that, sample Nº 1 and sample Nº 3 have exhibited higher fibre weight content, due to the better removal of excess resin impregnated in the fibres. According to received results it can be concluded that higher weight percent of fibres in final samples lead to better thermal stability of glass fibre reinforced composites.

B. *Hoop tensile modulus*

Determination of hoop tensile properties of filament wound composite tubular specimens by split disk method was one of the objectives of this paper. Four specimens were tested from each testing group. Mainly, the ultimate hoop tensile strength of the specimens were determined. In addition, the average of these results were calculated for each group, and with the aid of this data, the general behavior of the specimens was established. The apparent hoop tensile strength of the specimens was calculated by using (2):

$$\sigma = \frac{F_{max}}{2 \cdot A_m} \qquad (2)$$

In (2) σ is ultimate hoop tensile strength in MPa, F_{max} is maximum load prior to failure recorded in Newton (N), whereas A_m is minimum cross-sectional area of the two reduced sections by the sample, w x t, mm^2 (Fig. 4).

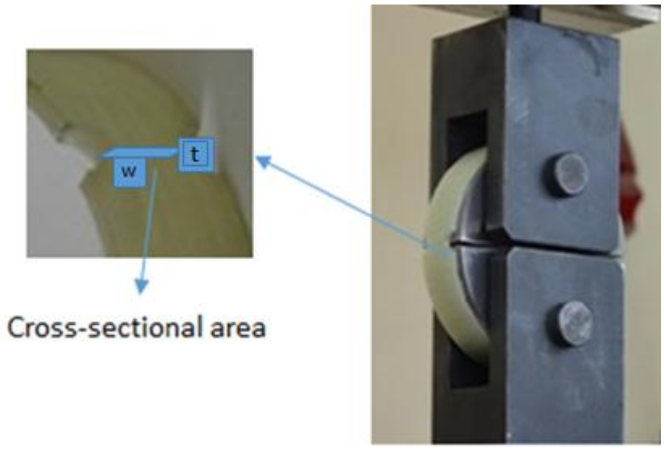


Fig. 4. Cross-sectional area of composite sample subjected under hoop tensile stress.

With conducted mechanical tests on filament wound rings hoop tensile modulus at ambient temperature was determined of all ring samples. The hoop tensile modulus was determined according to (3) or (4) [8]:

$$E_{\exp} = \frac{0.1257 r_{mean}^3}{wt^3} \frac{F}{\Delta} \qquad (3)$$

$$E_h = f \frac{d\sigma}{d\varepsilon} \qquad (4)$$

In (3), E_{exp} represent the hoop tensile modulus of ring sample in GPa, F is maximum load prior to failure in Newton (N), whereas t (mm) and w (mm) are the thickness and width of ring sample, respectively. r_{mean} (mm) is mean radius of manufactured ring sample.

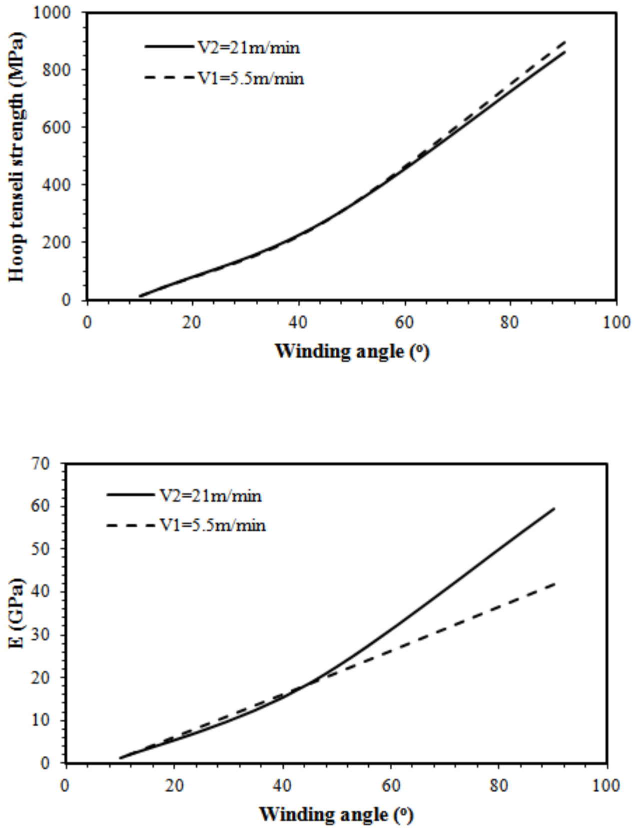


Fig. 5. Hoop tensile modulus of composite ring samples.

From received results given in Fig. 5 can be seen that the highest hoop tensile modulus has been presented by sample Nº 1 with bigger winding angle and winding speed. Sample Nº 2 has performed lower mechanical properties in comparison to radial wound sample. According to these results can be concluded that winding angle plays a major role in determination of mechanical properties in composite samples manufactured with filament winding technology. This mean that bigger winding angle (±90º) lead to higher hoop tensile modulus of filament wound composite structures when subjected under internal pressure [13-14].

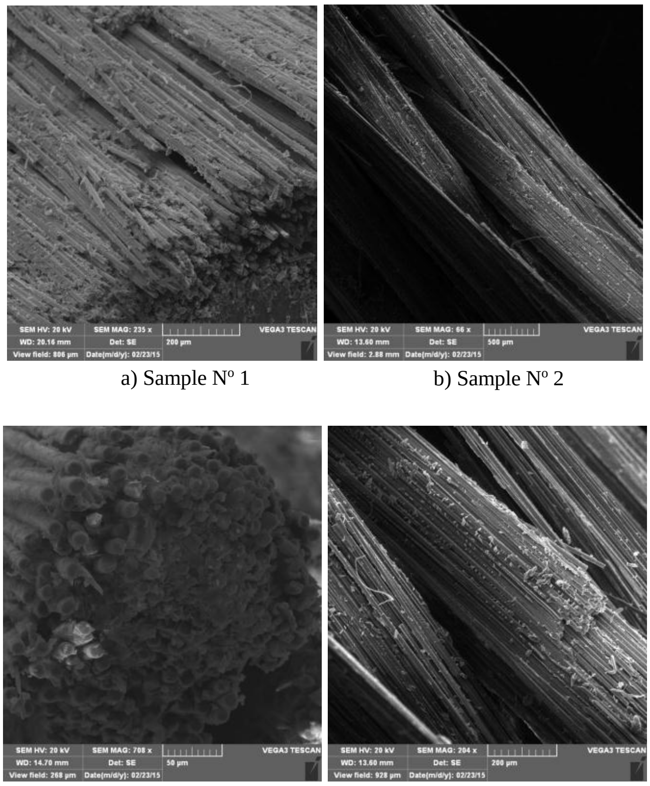
C. Scanning electron microscopy (SEM)

By all samples mechanical failure had occurred in line with the angle of winding. Mechanical failure of composite samples winded with different winding angle has been shown on Fig. 6.

Performed SEM analyses of already tested samples under hoop tensile strength are given on Fig. 7 where good merger between reinforcement and epoxy matrix can be seen. As failure mechanisms by all samples fibre-matrix debonding followed by matrix failure were detected. Delamination between layers was also detected by sample Nº 2 and sample Nº 4.

a) Sample Nº 1 b) Sample Nº 2

Fig. 6. Mechanical failure of filament wound composite samples.



a) Sample Nº 1 b) Sample Nº 2

c) Sample Nº 3 d) Sample Nº 4

Fig. 7. SEM analysis of tested filament wound ring samples.

IV. CONCLUSION

From conducted thermal analysis two stages of composite degradation were detected, one for the resin decomposition until 600ºC and the second one around 640ºC. According to received results, composites tubular samples winded with winding angle ±10º performed bigger weight lost in comparison to samples winded with winding angle ±90º. More specifically, composite samples winded with smaller winding angle have bigger weight percent of resin in comparison to samples winded with bigger winding angle. This can be contributed to the working princip of filament winding technique, where more tension is applied during radial winding which lead to remove of excess resin in the lower layers of composite structure compared to helical winding.

Performed mechanical tests lead to conclusion, that best results in tensile strength and hoop modulus can be obtained from composite pipes winded with angle $\pm 90^0$. When smaller angle is used ($\pm 10^o$), mechanical properties of composite samples decrease.

SEM analysis have confirmed good merger between fiber reinforcements and the matrix, whereas fiber-matrix debonding and matrix failure were detected as failure mechanisms. By samples winded with smaller winding angle ($\pm 10^o$), delamination between the layers was detected. Also, it was noted that all samples performed mechanical failure in line with the angle of winding.

The experimental procedure described in the present work is suitable to study the influence of winding angels and winding speed on thermal and mechanical properties of continuous glass fiber reinforced composites produced by filament winding technique. According to all conducted analysis in this investigation can be said that, significant differences in filament wound pipes wound with different fiber orientation can be seen which will determine the end application of this kind of products.

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