Vol. 11, 2022, 223-233

DOI: 10.17512/bozpe.2022.11.25

Construction of optimized energy potential
Budownictwo o zoptymalizowanym potencjale energetycznym

ISSN 2299-8535 e-ISSN 2544-963X

Effect of ply angle on the burst pressure of composite pressure vessels by filament winding

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Abstract: A composite pressure vessel is an important structure in different applications including pipes, pipes under pressure and closed system pipes under high pressure and temperature such as gas pipelines and aircraft structures, because of the characteristics of polymer – a composite used as an alternative to heavy materials such as metal in the various applications, including the construction industry. The current work focuses on the study of strength phase orientation and their properties on the burst pressure strength and other parameters, which are very important in the design and manufacture of these vessels such as the selection of type of strength phase nylon 6, 6 and philosophy of mixing of the type of fiber with matrix material (epoxy). The work also includes the study of the effect of two layer angle ply (0, 90), (55, –55), (75, –75) and implements different material testing to evaluate the toughness and stiffness of these vessels and compare the experimental result with the theoretical result. A filament winding apparatus was designed and executed to manufacture different types of subjects according to these angle of ply nylon fiber. The mechanical tests (tensile test, drop test, pipe stiffness test, hydrostatic pressure test) were used to test the vessel. The results shown that the ply orientation (75, –75) has high (tensile strength, toughness, stiffness, impact and burst pressure) when compared with the results from other ply orientations. This shows that [75, –75] ply orientation is the optimal angle for the vessel. Tensile tests show that (75, –75) ply orientation samples have higher properties in two directions, longitudinal and transverse, when compared with other angles.

Keywords: composite pressure vessels, filament winding angle, burst pressure

Please, quote this article as follows:

Saif T., Saad N., Al-Zubiedy A., Idzikowski A., Effect of ply angle on the burst pressure of composite pressure vessels by filament winding, Construction of Optimized Energy Potential (CoOEP), Vol. 11, 2022, 223-233, DOI: 10.17512/bozpe.2022.11.25

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Introduction

Composite materials typically provide a high possibility of producing construction that include enhanced mechanical performance, mainly with respect to specific stiffness, specific strength, damage tolerance, and energy absorption capability. Composite pressure vessels are a perfect example of the benefits that fiber-reinforced composite materials can give. They can be created from strong fibers in combination with a resin or plastic. The method of manufacturing composite pressure vessels is called filament winding. Composite pressure vessels were initially developed for aerospace applications (Al-Habahbeh & Al-Huniti, 2005; Balya, 2004; Kim et al., 2005; Önder, 2007; Yousefpour, 2002). Composite pressure vessels are used in numerous fields from households to industry to aviation. They are a critical component in numerous systems as their failure can lead to fatal accidents due to pressure differentials. One parameter amongst many that need to be calculated during design is burst pressure. Burst pressure is the point where the pressure in the vessel causes it to burst open/crack and internal liquid leak. A designed safety limit should not be exceeded. If the pressure is exceed it may lead to a mechanical breach and everlasting loss of pressure containment (Faramarzi & Kashani, 2015; Karpuz & Alpay, 2005; Njuguna, 2016; Pihtili, 2009; Reshma, 2017; Rubin, 1990; Tiwari, 2015; Vishwanath et al., 1992). Pressure vessels are created by winding large amounts of filament. Although they seem to be simple structures, pressure vessels are one of the most difficult to design. Filament-wound composite pressure vessels have found widespread use not only in the military, but conjointly for civilian applications. This type of technology, initially developed for military use, was adapted to civilian purposes and later extended to the industrial market. Applications include breathing devices, such as self-contained breathing apparatuses used by fire-fighters and alternative imperative personnel, scuba tanks for divers, oxygen cylinders for medical and aviation cylinders for emergency slide pumping, opening doors or lowering of landing gear, mountaineering expedition equipment, paintball gas cylinders … etc. (Abdelbary et al., 2014; Mark, 2007; Saad et al., 2017; Sikora et al., 1993). The current work focuses on the study of strength phase orientation and their properties on the burst pressure strength and other parameters, which are very important in the design and manufacture of these vessels such as selection of type of strength phase nylon 66 and philosophy of mixing of the type of fiber with the matrix material (epoxy).

1. Materials used and method

1.1. Sample preparation to production of composite pressure vessels

- NRP (nylon reinforce polymer) pipes were manufactured with several winding angles by using a filament winding machine (turning machine) [(0, 90), (55, –55), (75, –75)].
- The flexible aluminum pipe mandrel is fixed between two jaws. The flexible aluminum pipe helps with tying and untying aluminum pipe before and after winding, the winding system is shown in Figure 1.

Fig. 1. Winding system (*own photo*)

- Resins are mixed with hardener for 4-5 minutes to obtain the appropriate viscosity.
- The angle winding of fibers is delimited by the protractor above the mandrel and the fibers are wound above the mandrel as shown in Figure 2.

Fig. 2. Delimited angle and winding fiber (*own photo*)

- The resin is added to the fiber above the mandrel (Pre-impregnated winding) as shown in Figure 3.

Fig. 3. Resin added in external mold (*own photo*)

- The sample was cured for 24 hours at room temperature. Two layers of reinforced material provides a 3.2 mm thickness. The test specimen length is equal to 300 mm and the internal diameter was 43 mm as shown in Figure 4.

Fig. 4. Production of the pressure vessels (*own photo*)

- The weight of the fiber in the pipe sample before and after adding the resin and the volume friction of fiber by weight is shown in Table 1.

Table 1. Weight of fiber in the pipe sample before and after adding resin and the volume friction of fiber by weight (*own research*)

The angle of fiber	Weight of fiber before add [g]	Weight of fiber after add [g]	Volume friction of fiber
55	30.56	150.56	20.3%
75	70.75	190.75	37.2%
90	63.75	183.75	34.6%

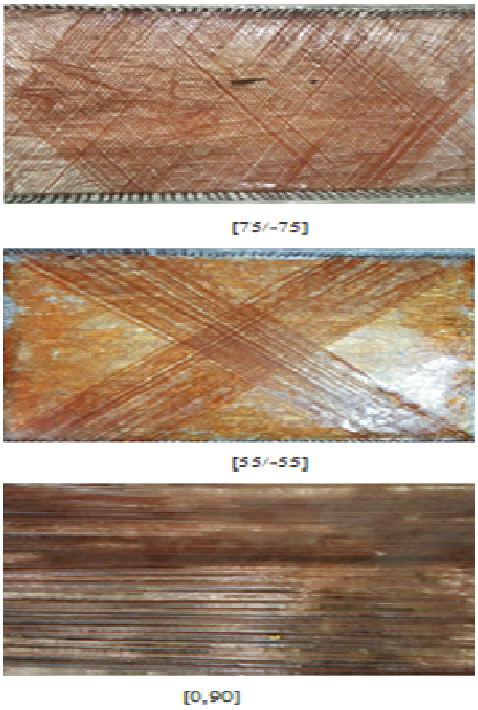
1.2. Production of the composite sheet

The composite sheet was prepare by the film stacking method. It consists of the following steps:

- Firstly, the wax was added to the mold to help release the product from the mold (Fig. 5). The mold was square and made from wood with a dimension of 28×28 cm, and a glass frame with thickness 2 mm fixed around the outside.

Fig. 5. Wax added to the wooden mold (*own photo*)

- Two layers of fibers were arranged at the suitable angle, and these fiber layers were fixed by nails in the wooden mold.
- Resin and hardener were mixed together for 4-5 minutes. Afterwards, the resin was applied to every layer using a brush.
- The mold was placed inside an electrical oven at 100°C for 30 min to get the required thickness. The composite sheet are release by removing the nails and the mold.
- The process was used to make two layers of composite sheet of different types (0, 90), (55, –55), (75, –75) as shown in Figure 6.



[75/-75]

[55/-55]

[0,90]

Fig. 6. Different composite sheets of various winding angle (*own photo*)

2. Experiment method

Tensile testing of the composite material was conducted according to ASTM D3039, the sample length = 250 mm and width of sample = 25 mm was used to determine mechanical property data. Uniaxial tensile force was applied to a flat test specimen to investigate the stress/strain behavior, load/deformation and critical materials properties including the tensile modulus in the axial and hoop direction, tensile strength, and elongation at break. The six samples used were (two samples from every sheet of composite material) tested in two directions. A highly precise universal testing device which consisted of a constant frame that made for compression testing or tension was used. The max load ability of the frame was 100 kN and the moving crosshead could be operated by two ball screws that were vertical placed in a system that used a drive with positional electronic servo control. The determination of mechanical properties, in particular the elastic moduli and tensile strengths of the anisotropic material, was more challenging. In order that the sheets manufactured simulated pipe design, the sheet samples were cut according to the pipe direction sample axial and hoop direction as seen in Figure 7.

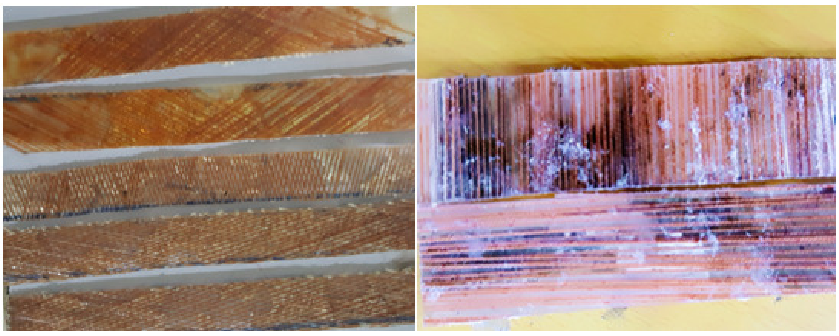


Fig. 7. Tensile test sample (*own photo*)

Burst pressure test: The interior pressure was conducted by a micro-processor controlled 100 bar XGY pipe hydrostatic testing machine. The method accounts for the variation in interior pressure by time through the test, until the specimen fractures, and so giving the bursting pressure. The determining process for burst pressure of a pressure vessel made from composite is dependent on the ISO 1167, ASTM D-1598 standard. The computer control model, high intelligence, real-time monitor, auto-recorder pressure force, and time are easy to operate and reliable. The pressure test system is shown in Figure 8.

Fig. 8. Specimen instrument matching (*own photo*)

3. Tensile result and discussion

In Figures 9 and 10 show the relationship between the load and deformation and the stress-strain relationship for an anisotropic plate manufactured to simulate a pipe design layer. The result of the tensile test in the figures present the axial direction. It is very clear that the relation between load-deformation is linear from the all samples in the prepared Series1, 2, 3 and that the applied load does not exceed the elastic deformation and there is no plastic deformation in the nylon reinforced polymer pipes. It is very clear that Series2 has highly elastic deformation and has a good load strength, high elastic modulus and that Series2 has high strength in both sides. The mix of toughness and strength in Series2 is due to the reinforcing of the polymer in these dimension. So that in transverse direction the nylon reinforced polymer exhibited average tensile strength values of 30 MPa for the ply orientation ±75 (Series2) greater when compared with ±55 (Series3) by 7 MPa and when compare with the (0, 90) ply orientation (Series1) 3 MPa greater. With increasing the angle configuration (helical angle) in the axial direction, the tensile properties increased.

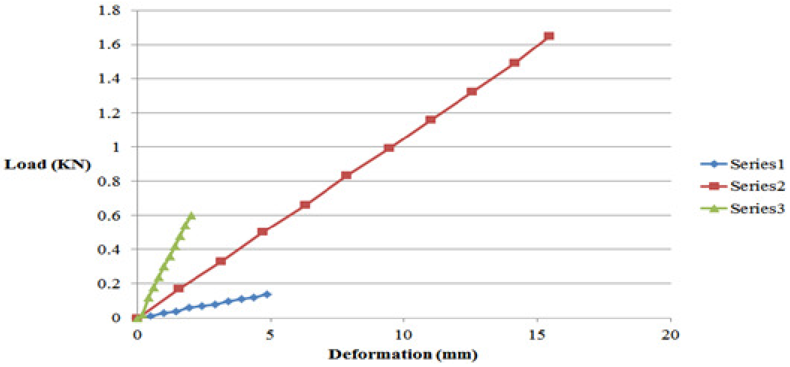


Fig. 9. Load – deformation of NRP in axial direction, where: Series1 has a load deformation of 0 ply orientation; Series2 has a load deformation of ±75 ply orientation; Series3 has a load deformation of ±55 ply orientation (*own research*)

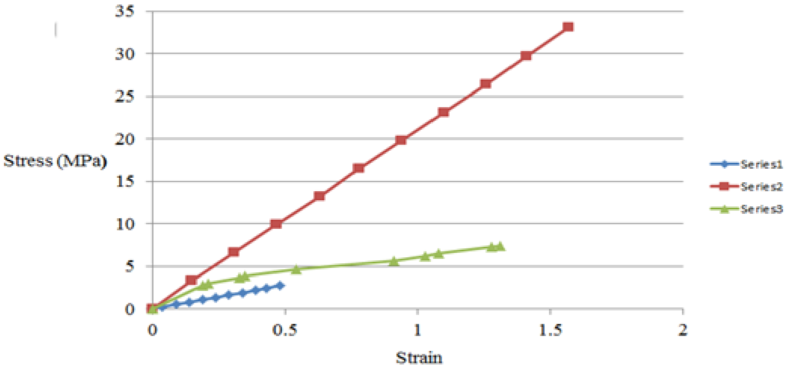


Fig. 10. Stress – strain of NRP in the axial direction, where: Series1 shows stress – strain in 90 ply orientation. Series2 shows stress – strain in ±75 ply orientation; Series3 shows stress – strain in ±55 ply orientation (*own research*)

From Figures 11, 12 which show the relationship between the load – deformation and stress – strain in the hoop direction of the sheet which simulates the pipe design, it is very clear that the relationship behavior is linear and there is no plastic deformation in this dimension. This behavior is very important for the stability of the pipes dimension in this direction. In the case brittle fractures (rigid pipe) for all the design samples of the pipe, the deformation in Series1 was greater than in the other Series2, 3. The strength increased in Series1 in the hoop direction, because of the effect of the fiber strength in the direction of applied load according to the rule of mixture: $E1 = E f_{\varphi} + (1-_{\varphi})\, E\, m$ (3), but the stress – strain and elastic modules behavior remained the same and little change was observed in Series1 which was greater than in Series2. Series3 had a higher value than the other series, because of the effect of the orientated area and length of the sample. As a result, in the hoop direction, the tensile strength values became 4 MPa for ±75 ply orientation, lower than when compared with ±55, which was found to be 5 MPa lower when compare with ±90, which was found to be 10 MPa.

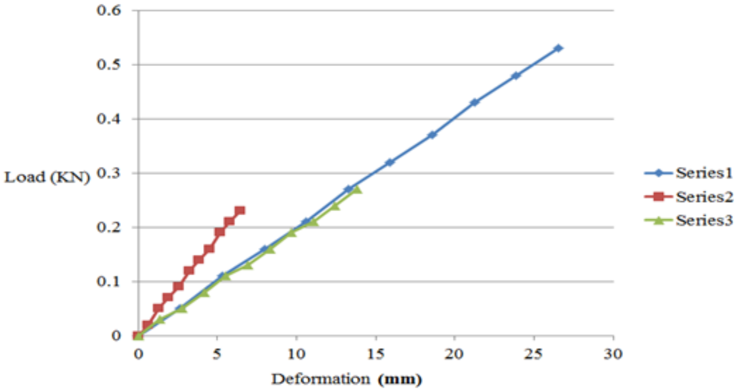


Fig. 11. Load – deformation curves of NRP in the hoop direction, where: Series1 has a load – deformation curve of ±90 ply orientation; Series2 has a load – deformation curve of ±75 ply orientation; Series3 has a load – deformation curve of ±55 ply orientation (*own research*)

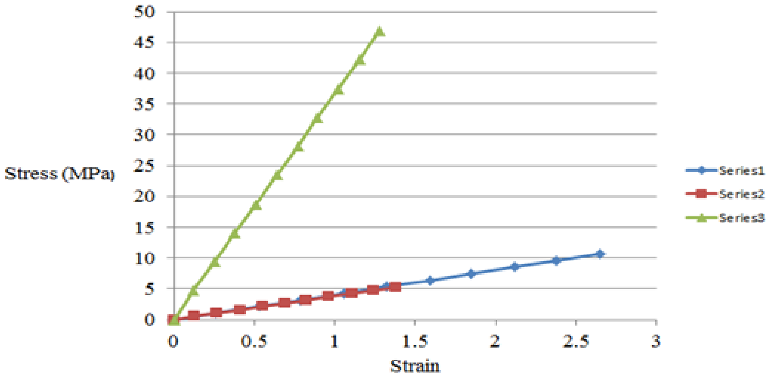


Fig. 12. Stress – strain curves of NRP in the hoop direction, where: Series1 has a stress – strain curve of ±90 play orientation; Series2 has a stress – strain curve of ±55 ply orientation; Series3 has a stress – strain curve of ±75 ply orientation; (*own research*)

4. Burst pressure result

The winding angle effects the burst pressure of the test tubes (Karpuz & Alpay, 2005). In order to decide the optimum winding angle, a winding angle was chosen between 0° and 90° (Önder, 2007). Figures 13-15, shown the burst pressure curve with time of different ply orientations. Table 2 shows the burst pressure in bars with different winding angles.

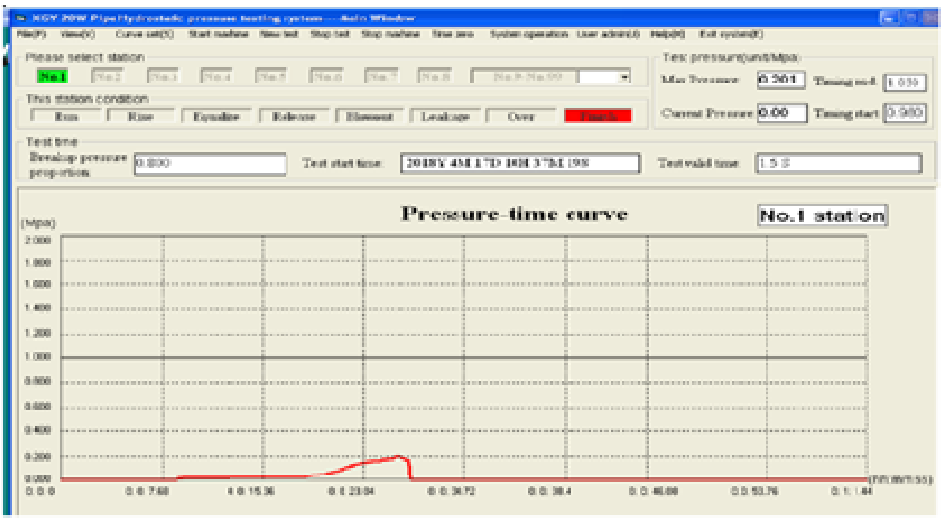


Fig. 13. Burst pressure test (0, 90) ply orientation pipe (*own research*)

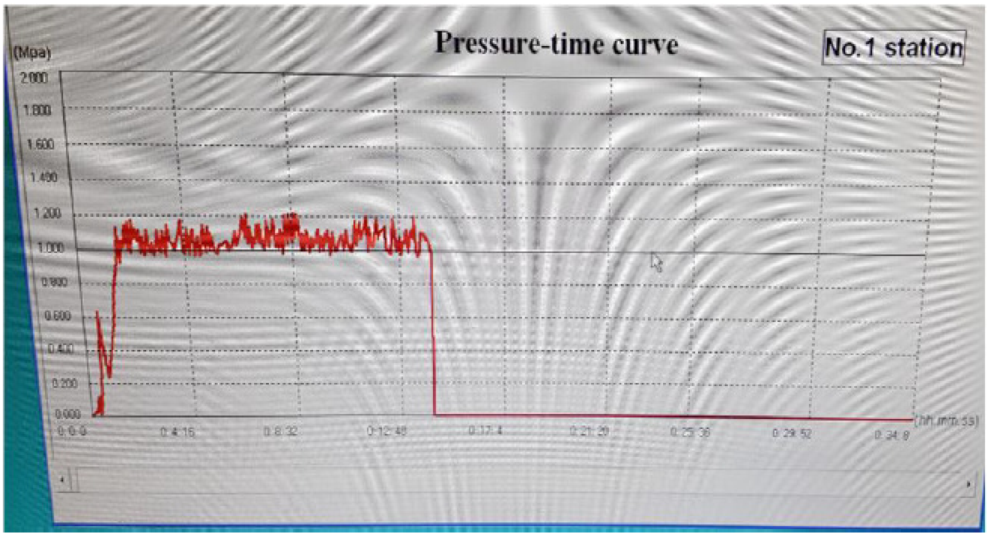


Fig. 14. Burst pressure test of ±55 ply orientation (*own research*)

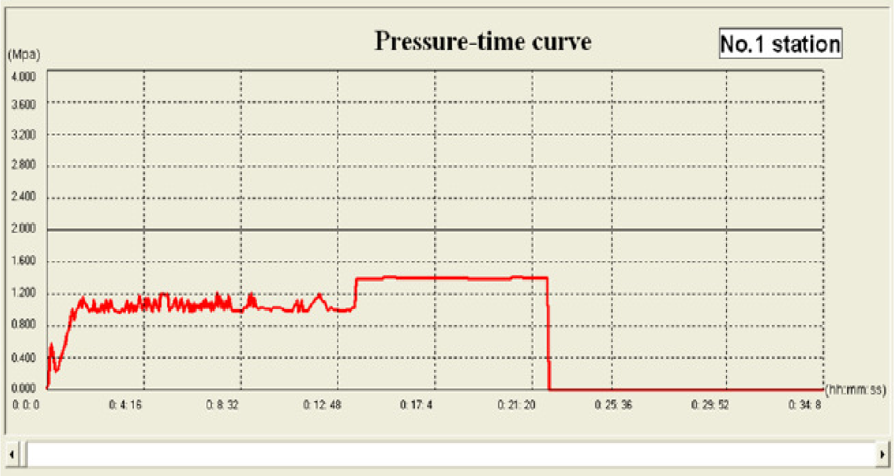


Fig. 15. Burst pressure test of ±75 ply orientation (*own research*)

Table 2. Burst pressure test in (bars) unit (*own research*)

Winding angle [°]	Burst pressure [bar]
90/90	2
+55/–55	12
+75/–75	14

Conclusion

The experimental work shows that the ultimate burst pressure becomes higher when increasing the winding angle because the filament angle increases the strength of the composite vessels. When the pressure vessels has winding at the hoop (0, 90) angle the burst pressure became 2 bars, when the pressure vessels winding angle equalled 55 the burst pressure was 12 bars, and when the pressure vessels winding equalled an angle of 75 the burst pressure was 14 bars and had high tensile properties. In conclusion, the 75 ply orientation is the optimal angle for pressure vessels.

Bibliography

Abdelbary, A., Abouelwafa, M. & El Fahham, I.M. (2014) Evaluation and prediction of the effect of load frequency on the wear properties of pre-cracked nylon 66. *Friction* 2(3), 240-254.

Al-Habahbeh, O.M. & Al-Huniti, N.S. (2005) Composite Pressure Vessels in Petroleum Industry. Status and Outlook, February.

Balya, B. (2004) Design and Analysis of Filament Wound Composite Tubes. December.

Faramarzi, I. & Kashani, M. (2015) Improvements in tribological properties of polyamide 6 by application of aramid pulp. *Iran Polym. J.*, 24, 329-335.

Karpuz, P. & Alpay, A. (2005) Mechanical Characterization of Filament Wound Composite Tubes by Internal Pressure Testing, May.

Kim, C.U., Kang, J.H., Hong, C.S. & Kim, C.G. (2005) Optimal design of filament wound structures under internal pressure based on the semi-geodesic path algorithm. *Composite Structures*, 67(4), 443-452.

Mark, J.E. (ed.) (2007) Physical Properties of Polymers Handbook. 2nd Edition, Polymer Research Center and Department of Chemistry University of Cincinnati, Cincinnati, Ohio.

Njuguna, J. (2016) Lightweight Composite Structures in Transport Design, Manufacturing, Analysis and Performance. Elsevier.

Önder, A. (2007) First failure pressure of composite pressure vessels. *Production of Composite Pressure Vessels*, 100-115.

Pihtili, H. (2009) An experimental investigation of wear of glass fibre-epoxy resin and glass fibre--polyester resin composite materials. *European Polymer Journal*, 45(1), 149-154.

Reshma, A.J. (2017) Review on burst pressure analysis of laminated composite pressure vessels. *International Research Journal of Engineering and Technology*, 4(5), 2738-2742.

Rubin, I. (1990) Handbook of plastic materials and technology. Wiley, New York.

Saad, N., Al-Zubiedy, A. & Mahmood M. (2017) Improvement mechanism of fracture toughness of HDPE with mixing mechanism (Nano particle) for pipe application. *International Journal of Applied Engineering Research* (*IJAER*), 12, 24.

Sikora, R., Flizikowski, J. & Al-Zubiedy, M.A. (1993) Effect of injection moulding parameters of toothed wheels and type of polyamide material on the kinematic gear ratio of a belt transmission with these wheels. *International Polymer Science and Technology*, 20, 4.

Tiwari, N. (2015) Manufacturing of Thermoset Composites, 11.

Vishwanath, B., Verma, A. & Kameswara Rao, C. (1992) Effect of matrix content on strength and wear of woven roving glass polymeric composites. *Composite Science and Technology*, 44(1), 77-86.

Yousefpour, R. (2002) Epoxy Woven Composite Material for a Semi-Autonomous (Vol. 36).