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Study of the winding methods influence on the aramid fibers impregnation degree for high-pressure pipes manufacturing

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Abstract: The purpose of this work is to compare the impregnation degree of samples made from an aramid-polyurethane composite material produced by three methods of winding. The para-aramid impregnation degree assessment was made on the basis of a microscopic examination of a sample’s section, as well as the results of determining the delamination fracture toughness of ring samples. Based on the studies, it was concluded that the best impregnation degree for para-aramid fibers is achieved in case of using binder sputtering assisted dry winding technology. This technology can be used for high-pressure flexible pipes manufacturing to increase their strength, which can lead to the product’s working pressure increasing.

Key words: Polymer composite materials, aramid fibers, polyurethanes, flexible pipes, composite technologies, winding.

1. Introduction

The main requirements for high pressure pipes are flexibility and strength [1]. It is impossible to use traditional materials such as reinforced rubbers or unreinforced organic materials to achieve the maximum possible values at the same time, that’s why you have to choose between strength and flexibility [2]. Composite materials make it possible to achieve the values of these characteristics in products manufactured on their basis.

Aramid fibers were chosen as the reinforcing material, due to their extremely high tensile strength values [3,4], which makes it possible to create pipes that can withstand higher pressures compared to flexible pipes based on reinforced rubber [5].

The matrix material is a urethane prepolymer based on polyether and toluene diisocyanate (TDI) [6]. Since this urethane composition has a rather high elongation at break (up to 470% when using the hardener URELINK-121) in combination with tensile strength indicators similar to epoxy resins (46-48 MPa), this allows it to be used as a binder for flexible high-pressure pipes. Also, this polyurethane composition has chemical resistance to many aggressive environments, such as: heptane, kerosene, mineral oils, hydrogen peroxide and others [7,8].

However, in addition to the high strength of aramid fibers, and the high break elongation of polyurethane, these materials have several disadvantages. One of the main disadvantages of para-aramids is a bad wettability, which is a consequence of its poor impregnation degree [9]. In combination with the high viscosity of polyurethanes (compared to the most epoxy resins), this property of aramid fibers makes it even more difficult to obtain bonded components of the compositions.

To eliminate this disadvantage, sizing compositions, plasma treatment, and ion etching are used [10-12]. All of these methods increase the adhesive interaction of aramid fibers with polymer binders.
But fiber processing is not the only factor affecting the degree of fiber impregnation. Also, the technology and conditions for combining the matrix and filler are important [13-15]. Winding was considered as a technology for manufacturing high-pressure pipes, because it is the most optimal method for manufacturing bodies of revolution from composite materials.

2. Technologies of flexible pipes winding

The most accessible and proven technology for flexible pipelines manufacturing based on aramid-polyurethane composition is winding. The main essence of the winding process is that the reinforcing material is wound on a rotating mandrel [16,17]. The availability of the technology is caused by the fact that instead of the special winding equipment there can be used lathes modified by installing means of automation (CNC) on them.

![Figure 1. Experimental winding machine](image)

The equipment required to implement the winding technology system consists of:

- winding machine;
- tension roller system;
- creel;
- containers for impregnation with a binder (in case of wet winding);
- systems for applying a binder to a reinforcing filler.

It should be mentioned that winding is not a one specific technology, but is a group of technologies that are similar in essence, but different in implementation. In this study there were considered three technology variations, differentiated by the method of binder applying.

1. Fiber winding with layer-by-layer spraying of a binder using a spray gun (Technology #1 - “Binder sputtering assisted dry winding”);

2. Fiber winding that has passed through the container with the binder (Technology #2 - “Wet winding”);

3. Prepreg winding [18] (Technology #3);
Advantages and disadvantages of each winding technology are presented in Table 1.
### Table 1. Summary table of considered winding technologies

| Technology #1 | Technology #2 | Technology #3 |
|---------------|---------------|---------------|
| **Advantages** | **Advantages** | **Advantages** |
| + absence of premature binder hardening due to components’ mixing, occurring immediately before its application; + guaranteed fibers’ impregnation with binder | + more sparing binder consumption (comparing to the Technology #1) due to the recycling system represented by surplus binder removing rollers | + the most sparing binder consumption among all these technologies; + cleanliness during work |
| - binder overconsumption; - the technology is dirty and requires equipment isolation covering and/or binder recycling system installation | - premature binder polymerization in the resin resin tank in case of emergency situation; - requires equipment isolation from the falling drops of resin | - complicity of prepreg’s preparation: the need of automated prepreg manufacturing line and storing refrigerators installing |

According to described methods of winding were made six thin-walled ring specimens: three for studying the tensile strength, three for studying the microstructure of the material.

### 3. Material microstructure research

The microstructure of the composite material was examined using a universal Vision Engineering TIM5 microscope [19]. Samples of the impregnated composition were cut along the generatrix, transversely to the direction of the fiber winding. The microstructure of the material produced by binder sputtering assisted dry winding, wet winding and prepreg winding are shown in Figures 5, 6 and 7, respectively.

![Figure 5. Microstructure of samples produced by binder sputtering assisted dry winding technology](image)

![Figure 6. Microstructure of samples produced by wet winding technology](image)
Figure 7. Microstructure of specimens produced by prepreg winding technology

4. Experimental determination of delamination fracture toughness

To position the crack in the material, the pieces of fluoroplastic film were located between the layers of the composite [20]. Further, samples were cut along the generatrix in the film laying area, and two edges of material around the crack were fixed in the clamps of the testing machine. The tests were carried out under continuous loading at a speed of 50 mm/min. The test results are presented in Table 2.

Table 2. Delamination fracture toughness determination tests results

| Technology                      | Specimen number | F, N | G, kJ/m² |
|---------------------------------|-----------------|------|----------|
| Binder sputtering assisted dry winding | 1                | 102  | 10       |
|                                 | 2                | 99   | 10       |
|                                 | 3                | 105  | 11       |
| Wet winding                     | 4                | 87   | 9        |
|                                 | 5                | 74   | 7        |
|                                 | 6                | 91   | 9        |
| Prepreg winding                 | 7                | 95   | 10       |
|                                 | 8                | 98   | 10       |
|                                 | 9                | 92   | 9        |

5. Conclusion:

Considering the aramid-polyurethane composition microstructure analysis, as well as the results of delamination fracture toughness testing, it was found that the highest degree of impregnation and strength during delamination is provided by the binder sputtering assisted dry winding technology. Based on the results obtained, this technology can be recommended as the most preferable for the flexible high-pressure pipes manufacturing.
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