

# FIBERGLASS PIPELINE CONTINUOUS FILAMENT WINDING AUTOMATION

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**Abstract** – The fiberglass composite materials in many ways solve the problems of operation and maintenance of pipelines in various industries and municipal services. Continuous filament winding is a progressive production method with a high degree of automation. It is necessary to take into account the complex influence of the technological parameters of the used winding method when designing the product structure. The actual problem of creating specialized equipment with continuous axial movement of the wound product is considered. Continuous winding ensures a constant product structure along its entire length. A study of a model for the formation of the structure of a fiber-reinforced pipe during continuous oblique-layer longitudinal-transverse winding is presented. Several types of devices providing the ability to perform continuous filament winding automation have been studied. Mathematical equations for the control parameters of these devices depending on the technological parameters of the winding process are obtained. The possibility of forming a pipe wall thickening in given areas while maintaining the reinforcement structure is shown. Examples of created automated continuous pipe winding equipment are given. A two-level CNC system with coupled control is used to control the equipment. The proposed solutions ensure stable reproduction of the reinforcement structure in modern pipe production conditions.

**Keywords:** CNC, Filament Winding, Automation, Fiberglass Reinforced Plastic, Continuous Manufacturing Technology.

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## 1. Introduction

The use of fiberglass composite materials for pipeline manufacturing as part of the infrastructure of the oil and gas and chemical industries, as well as municipal services, largely solves the problems of their operation and maintenance [1–3]. Filament pipe winding technology is an advanced production method with a high degree of automation [4–6].

It is necessary to take into account the complex influence of the technological parameters of the used winding method, or helical winding on a rigid mandrel or continuous winding on a feed mandrel when product structure design [7]. For example, to control the volumetric filling of a structure, it is important to ensure the necessary tension of the fiber by laying transverse layers [8, 9]. The tensions of the surface and internal layers can differ significantly due to helical winding, resulting in deviations of the stress-strain state from the design values [10, 11]. Helical winding creates reversal zones with a disrupted material structure, while continuous winding ensures a

constant structure of the product along its entire length.

The automation of the winding process is determined by the type of used winding system, for example, based on lathe [12, 13] or robotic equipment [14, 15]. The creation of specialized equipment with continuous axial movement of the wound product is relevant. Such equipment must ensure the comprehensive implementation of all processes that create the product, for example, laying auxiliary materials and functional layers, forming the main structural layer with a given structure [16, 17]. Various types of general industrial and specialized control systems are used to control equipment [18, 19].

Thus, pipelines' continuous winding process automated control is an urgent scientific and industrial problem. This paper presents an investigation of a model for the fiber-reinforced pipeline structure formation, the equipment used for continuous winding of the pipeline, numerical program control of this process, as well as the implementation of this technology in production.

## 2. Fiber-reinforced Pipeline Structure Formation by the Oblique Longitudinal-Transverse Winding Method

To ensure the strength and tightness of pipelines in the oil and gas and chemical industries, as well as public utilities, it is necessary to form a certain cross-sectional structure of the pipe. For the problem of water, oil products, and aggressive liquids transporting under high pressure, it is necessary that at least two layers be formed in the cross-section of the pipe – a sealing layer and a structural layer (Fig. 1).

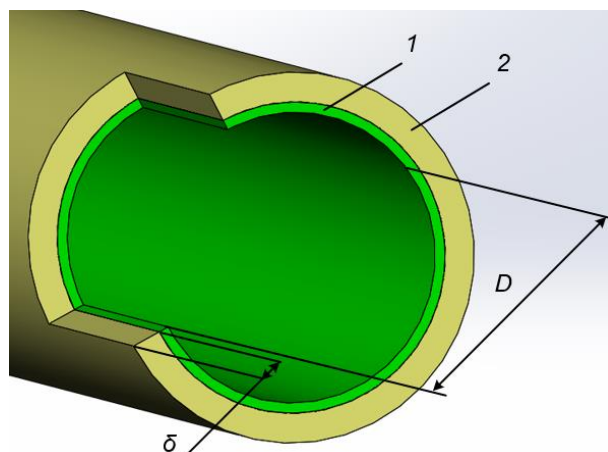


Figure 1: Pipe cross-section structure: 1 is the sealing layer; 2 is the structural layer

The sealing layer is formed by laying a sealing tape on the mandrel. To form a structural layer, the paper proposes a method of continuous oblique-layer longitudinal-transverse winding. The layout of the structural layer filaments is shown in Fig. 2. In the considered method, two types of filament with significantly different angular orientations relative to their axis are wound onto a mandrel. In the considered process, filaments of transverse orientation with number  $m$  (Fig. 2, pos. 1) are located perpendicular to the axis of the mandrel. Filaments with longitudinal orientation (Fig. 2, pos. 2) are located at a slight angle to the longitudinal axis of the mandrel ( $\alpha$ ). Longitudinal reinforcement filaments are supplied to the winding zone in the form of a flowline formed on auxiliary filaments (Fig. 2, pos. 3). The width of this flowline determines the size of the laying base ( $L$ ). The number of longitudinal reinforcement filaments supplied to the winding zone depends on the stacker rotation speed using the rotation of the stacker (Fig. 2, pos. 4). The mandrel (Fig. 2, pos. 5) ensures continuous displacement of the wound pipe with a feed  $F$  for each revolution of the mandrel.

The layout of reinforcing layers along the thickness of the pipe is shown in Fig. 3. With this laying scheme, the pipe wall thickness  $\delta$  is formed by several layers located at an angle to the pipe axis.

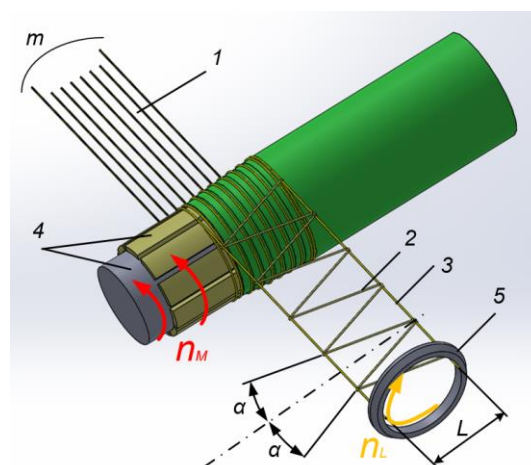


Figure 2: Filament laying pattern: 1 is the transverse reinforcement filaments; 2 is the longitudinal reinforcement filaments; 3 is the auxiliary filaments; 4 is the longitudinal filament stacker; 5 is the mandrel

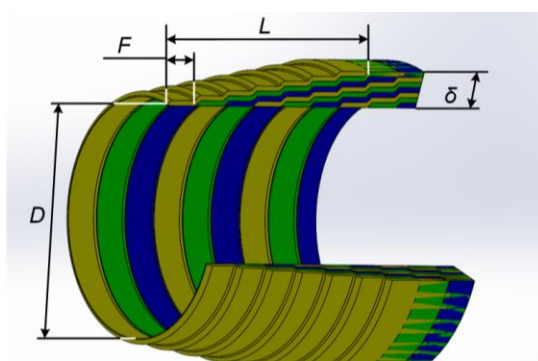


Figure 3: Reinforcing layers scheme layout along the wall thickness

The laying angle of the layers is determined by the ratio of the laying base  $L$  and the wall thickness  $\delta$  of the wound pipe. At each revolution of the mandrel, a monolayer with a given reinforcement structure is formed. Each subsequent monolayer is displaced relative to the previous one by the amount of longitudinal feed  $F$  along the mandrel.

The winding process in question theoretically forms an endless pipe, but in the actual manufacturing process, the pipe is cut into finite-length sections. It is necessary to form thickenings of the pipe wall in given areas to connect pipes. Variation of feed  $F$  allows for adjustment of the pipe wall thickness while maintaining the structure of the reinforcing fibers. This factor makes it possible to produce glass-reinforced pipes with thickened walls in a continuous process. The mechanical characteristics of the pipe material depend on the location of the reinforcing fibers.

The anisotropy coefficient  $k$  quantifies differences in performance in the longitudinal and transverse directions. With the same linear density of transverse and longitudinal fibers, the anisotropy coefficient  $k$  is equal to the ratio of their volumes in

the material structure and is determined by the equation:

$$k = \frac{m}{m_L}, \quad (1)$$

where  $m$ ,  $m_L$  are, respectively, the number of filaments in the transverse and longitudinal directions in the monolayer.

The number of longitudinal reinforcement filaments in a monolayer  $m_L$  depends on the effective diameter of winding on the mandrel  $D_M$ , the length of the winding base  $L$ , and is determined by the equation:

$$m_L = \frac{2L}{\pi D_M} \cdot \frac{n_L}{n_M}, \quad (2)$$

where  $n_L/n_M$  is the ratio of the number of revolutions of the longitudinal reinforcement layer per one revolution of the mandrel.

Using Eq. (2) we express the anisotropy coefficient through technological parameters characteristic of the method of continuous oblique longitudinal-transverse winding:

$$k = m \cdot \frac{\pi D_M}{2L} \cdot \frac{n_M}{n_L}. \quad (3)$$

The coefficient  $k$  is selected based on the operating conditions of the pipe and the required mechanical characteristics.

The process of laying longitudinal filaments involves their positioning at a small angle  $\alpha$  to the mandrel axis (Fig. 2). Let's write down equations relating this angle to the technological parameters of the winding zone:

$$\begin{aligned} \cos^2 \alpha &= \frac{L^2}{L^2 + \left(\frac{\pi D_M}{2}\right)^2 \cdot \left(\frac{n_M}{n_L}\right)^2}, \\ \sin^2 \alpha &= \frac{\left(\frac{\pi D_M}{2}\right)^2 \cdot \left(\frac{n_M}{n_L}\right)^2}{L^2 + \left(\frac{\pi D_M}{2}\right)^2 \cdot \left(\frac{n_M}{n_L}\right)^2}. \end{aligned} \quad (4)$$

Let's take

$$a = \left(\frac{\pi D_M}{2L}\right)^2, b = \left(\frac{n_M}{n_L}\right)^2. \quad (5)$$

Thus,

$$\cos^2 \alpha = \frac{1}{1+ab}, \sin^2 \alpha = \frac{ab}{1+ab}, k = m\sqrt{ab}. \quad (6)$$

Hence

$$\frac{n_L}{n_M} = m \cdot \frac{\sqrt{a}}{k}. \quad (7)$$

The stability of the wall structure is determined by the constancy of this ratio over the entire length of the wound pipe. Thus, to implement the process of continuous oblique-layer longitudinal-transverse

winding, the equipment and control system must provide a given ratio  $n_L/n_M$ .

### 3. Continuous Winding Equipment Scheme

To implement the continuous winding process, it is necessary to implement several processes together: rotation and longitudinal movement of the wound product; winding the sealing tape; winding longitudinal and transverse fibers. The general scheme of the equipment for continuous winding of the pipeline is shown in Fig. 4.

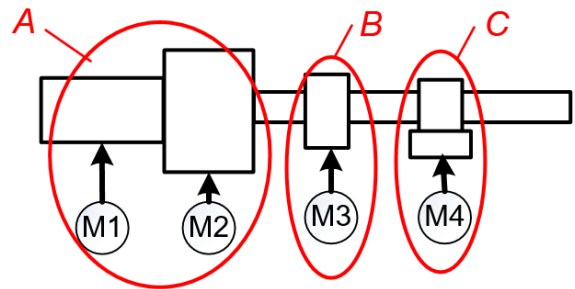


Figure 4: Continuous pipeline winding equipment scheme: A – self-feeding mandrel drive; B – drive of the sealing layer stacker; C – drive for laying the structural layer

Rotation and longitudinal movement of the product are provided using a multi-sector self-feeding mandrel, the drive scheme of which is shown in Fig. 5. The mandrel is a mechanism consisting of a central body (Fig. 5, pos. 1) and a system of sectors (Fig. 5, pos. 2) that can move along the axis of the mandrel by a limited amount ( $K_n$ ).

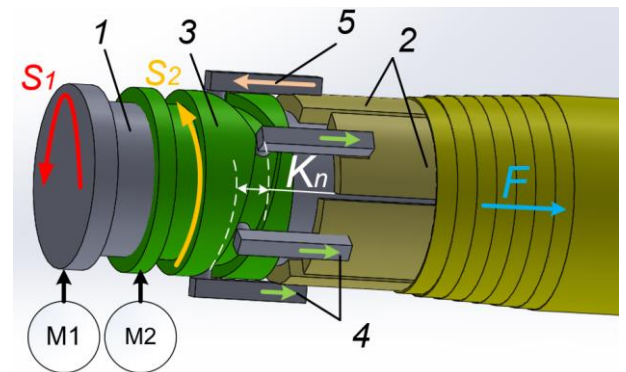


Figure 5: Self-feeding mandrel drive scheme

Drive M1 provides the main forming movement - rotation of the mandrel. The movement of all other organs is associated with the rotation of the mandrel in various ratios.

The longitudinal movement of the product ( $F$ ) is ensured by the reciprocating movement of the mandrel sectors, while most of the sectors move in the feed direction (Fig. 5, pos. 4), and the smaller part in

the opposite direction (Fig. 5, pos. 5). This movement is set by a special copier (Fig. 5, pos. 3) with an M2 drive.

The longitudinal pipe flow corresponds to the equipment productivity and is determined by the equation

$$F_n = S_1 \cdot F, \quad (8)$$

where  $F_n$  is the longitudinal pipe feed [mm/min],  $S_1$  is the mandrel rotation speed [rpm],  $F$  is the pipe feed per revolution [mm/rev].

The longitudinal pipe feed is formed due to the difference in the rotation speeds of the mandrel and the copier:

$$F_n = (S_1 - S_2) \cdot K_n \quad (9)$$

where  $S_2$  is the copier rotation speed [rpm],  $K_n$  is the copier step [mm/rev].

The copier step  $K_n$  corresponds to the feed per one revolution of the copier relative to the mandrel. From Eqs. (8) and (9), obtain the rotation speed of the copier  $S_2$ , which provides a given longitudinal feed  $F$  depending on the rotation speed of the mandrel:

$$S_2 = \left(1 - \frac{F}{K_n}\right) \cdot S_1. \quad (10)$$

In contrast to the structural layer, which is formed by winding fibers, the sealing layer is formed by winding a special tape onto the surface of the mandrel. The drive diagram of the sealing layer stacker is shown in Fig. 6.

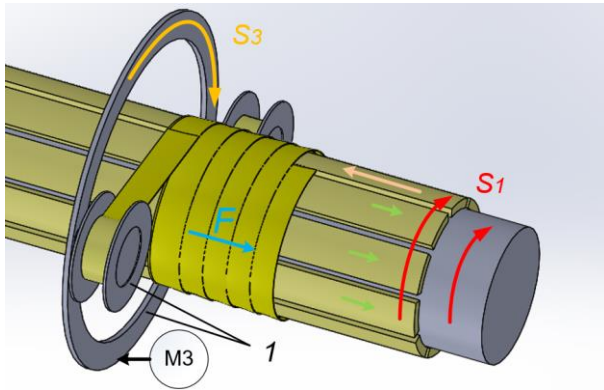


Figure 6: Stacker drive scheme for sealing layer

The M3 drive ensures rotation of the sealing layer stacker (Fig. 6, pos. 1). The rotation speed of the stacker relative to the mandrel must ensure the specified laying step of the sealing layer  $F_{SL}$  [mm/rev] and ensure the layer winding performance corresponding to the general process:

$$F_n = S_{SL} \cdot F_{SL} \quad (11)$$

where  $S_{SL}$  is the relative rotation speed [rpm].

Using Eq. (8) and (11), obtain the equation

$$S_{SL} = \left(\frac{F}{F_{SL}}\right) \cdot S_1. \quad (12)$$

The relative rotation speed  $S_{SL}$  of the stacker is the difference between the rotation speed of the mandrel and the rotation speed of the stacker sealing layer:

$$S_{SL} = S_1 - S_3, \quad (13)$$

hence

$$S_3 = \left(1 - \frac{F}{F_{SL}}\right) \cdot S_1. \quad (14)$$

The main structural layer is formed using the method of continuous oblique longitudinal-transverse fiber winding. The basic relations between technological parameters were discussed in detail in the previous section. To carry out fiber winding in accordance with the scheme shown in Fig. 2, the equipment structure includes an M4 drive. It provides rotation for the longitudinal reinforcement fiber stacker. The rotation speed of the stacker is set through the parameter of the transmission ratio of the stacker rotation to the rotation speed of the mandrel when setting the parameters of the winding technological process and, taking into account Eq. (7), is determined by the equation:

$$S_4 = \left(\frac{n_L}{n_M}\right) \cdot S_1 = m \cdot \frac{\sqrt{a}}{k} \cdot S_1. \quad (15)$$

Thus, the kinematic schemes of the drives of the continuous pipe winding installation have been considered and the movement parameters of each drive have been determined depending on the main movement – the rotation of the mandrel. This makes it possible to generate initial data for coordinated control of four drives, ensuring: rotation of the mandrel at speed  $S_1$ ; constant forward movement of the wound pipe with feed  $F$ ; winding of the sealing layer tape with  $F_{SL}$  feed; winding of the main structural layer on the base  $L$ , ensuring wall thickness  $\delta$ .

#### 4. CNC Structure and Winding Process Programming

One of the possible control schemes for continuous pipe winding is shown in Fig. 7. The initial information as a set of parameters for setting the movement modes of the devices involved in the formation of the pipe structure is transferred to the CNC in the form of a G-code compatible file. For experimental investigation, the authors use a two-level CNC system [20, 21], in which code interpretation and mo-

tion interpolation are distributed between two computers. The “interpreter” transforms the data and generates “machine code” in a format convenient for equipment control, which does not require real-time mode.

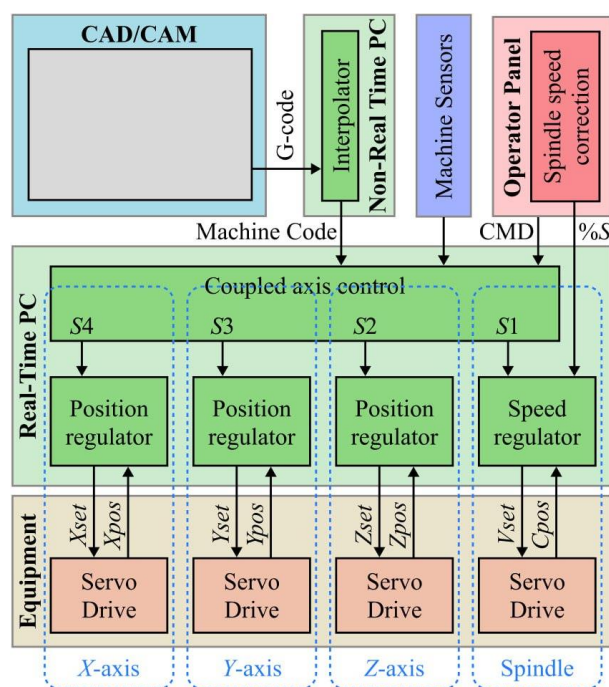


Figure 7: Winding control organization

The “Interpolator” and “Regulator” operate in real-time and are clocked at different rates to eliminate “information hunger”. Variations in position and speed are transmitted by the “Interpolator” to the “Regulator” in normal mode for each control cycle.

The logic of the relationship between the movements of all devices involved in winding, discussed in the previous sections, implies that in the structure of the machine, only one device is independent – the mandrel drive. All other types of devices, such as the copier, seal layer stacker, and longitudinal reinforcement fiber stacker are axes of this coupled control. Accordingly, when setting up the control system, the mandrel is defined as the main spindle, and all other devices are defined as coupled control axes with their own communication functions and a set of parameters and addresses for their programming.

It should be noted that all slave devices are controlled in position control mode with tracking of the mandrel movement. This control scheme guarantees stable reproduction of a given reinforcement structure.

Section 2 noted the need to thicken the wall in certain areas, which may be necessary for subsequent connection of pipes or installation of fixing elements during pipeline installation. The equipment programming system for each device provides at least two operating modes – main and additional.

The rotation speed of the mandrel  $S_1$  is programmed as the main movement at address  $S$ , and the feed of the pipe along the mandrel is programmed at address  $F$ . Below is a listing of a program designed for dual-mode pipeline winding. The main mode sets the winding parameters for a regular section of the tube, and the additional mode sets the parameters for obtaining a thicker wall.

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%
/ Pipe-100-3.4-...
/ BASIC WINDING MODE
S20 / Mandrel rotation speed rpm
F5.2 / Pipe feed, mm/rev
FLAYER = 25 / Step of laying the sealing
layer, mm/rev
NYLOPR = 9.52 / Gear ratio of longitudi-
nal reinforcement stacker
/ ADDITIONAL WINDING MODE
S_D = 20 / Mandrel rotation speed, rpm
F_D = 2.5 / Pipe feed, mm/rev
FLAYER_D = 25 / Step of laying the seal-
ing layer, mm/rev
NYLOPR_D = 9.52 / Gear ratio of the FIRST
longitudinal reinforcement stacker
m30
%
    
```

The applied control system ensures the activation of winding parameter settings when loading the program for execution. The winding process itself and changes or adjustments to its modes are carried out after receiving the appropriate CMD commands coming from the operator console or machine sensors (Fig. 7). In Fig. 8 shown is a sample of a pipe with a thickening section, manufactured according to the above program.



Figure 8: Section of the wall thickening of a fiber-reinforced pipe

## 5. Technology Implementation

The developed schemes and algorithms are implemented in a series of installations for continuous winding of pipes with standard sizes of 20...100 mm, 100...300 mm, and 300...800 mm at the Research-and-production Company “Plastar” LLC (Fig. 8–10).

The formation of the pipe structure is shown in Fig. 9.



Figure 9. Equipment for continuous winding of pipes of standard size 300...800



Figure 10: Pipe structure formation

The use of the above-automated equipment allows us to produce pipes with an optimal reinforcement structure and thickenings for joints in a continuous process. In this case, the structure of the thickening is similar to the structure of the regular part of the pipe, which is especially important for highly loaded tubing pipes.

In Fig. 11 and 12 shown pipes with a diameter of 25 and 80 mm, manufactured for the installation of gas and geothermal wells.



Figure 11: Fiberglass pipes with a diameter of 80 mm for geothermal wells



Figure 12: Fiberglass pipes with a diameter of 25 mm for gas well

## 6. Conclusions

The paper discusses the current problem of creating automated equipment for continuous winding of fiberglass pipes. It has been analytically proven that the stability of the structure of the pipe wall is determined by the constancy of the number of rotations of the layer per one revolution of the mandrel and must be ensured during the operation of the equipment. Kinematic schemes of the drives of the continuous pipe winding equipment are considered and mathematical models of the movement of each drive are developed depending on the main movement of the mandrel. The models make it possible to generate initial data for the coordinated control of four drives. To control the equipment, a two-level CNC system was used. An example of a program for continuously winding a fiberglass pipe with thickening in an arbitrary section is presented, which is necessary for designing the connection of pipeline parts. Examples of installations for continuous winding of pipes with standard sizes 20...100 mm, 100...300 mm, 300...800 mm at Research-and-Production Company "Plastar" LLC are shown. Automated equipment is used for the continuous winding of high-load tubing. Examples of highly loaded tubing production technology implementation are shown, in particular, the use of a fiberglass pipe with a diameter of 25 mm for gas well installation and a fiberglass

pipe with a diameter of 80 mm for the geothermal wells installation is shown.

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