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WINDING OF CYLINDRICAL PRODUCTS AND CURVED BARS OF REINFORCED POLYETHYLENE TEREPHTALATE

The fundamentals are developed, regularities are analyzed and patterns are estimated of one-step process of winding cylindrical and curved products from recycled PET. Experimental samples of cylindrical and oval products are obtained. The method for estimation of parameters of the winding process by criteria impregnation and consolidation. The method developed can be used to determine the optimal mode of winding cylindrical and curved reinforced tape products based thermoplastics.

Introduction. One of the most promising high-shaping processes of products from reinforced thermoplastics with oriented structure is winding. Pressure vessels and pipes for chemical, oil and other industries can be obtained by winding. Furthermore, existing products such as pressure vessels, extinguisher cylinders, etc. can be reinforced with hoop and spiral winding. Two-stage and single stage of winding are known [1]. By the two-stage embodiment at first the thermoplastic matrix polymer is combined with a fiberfill on powder, fiber or melt technology preparing unidirectional tape, which is then wound onto arbor by heating to the melting temperature of the matrix polymer and combining with the previously overlays. Heating and consolidation of tapes are carried out directly during installation.

By single stage technology tape is wound on the arbor. The tape is prepared combining fibrous filler and the polymer melt with the same process installation (“on-line” – “in line”) immediately prior to winding. Additional heating to consolidate the material is not required. This reduces the disrupt thermal impact on the polymer. Power inputs and cost of technological equipment reduce, processing efficiency increases and the cost of production becomes cheaper.

Obviously, in terms of energy consumption and cost reduction one-stage option is more profitable. However, by one-stage winding it is necessary to combine three processes – impregnation, shaping and consolidation – in accordance with the main process parameters, primarily temperature and power velocity. At the same time the requirements for the viscous properties of the matrix polymer and the prepreg at various stages of the process are contradictory.

The paper aims at estimating the parameters of a single-stage winding of cylindrical products and curved bars from reinforced polyethylene terephthalate.

Main part. The investigation was aimed on the one-step process of winding tape based on recycled polyethylene terephthalate (PET) and glassroving EC 13-2400 (content by weight (45 ± 5)%) on the polyethylene pipe with a diameter of 90 mm and a length of 200 mm used as arbor. Fig.1 shows experimental production line, on which the process of winding cylindrical products and curved rods were investigated.The line is installed on the base of pultrusion in a laboratory of composite materials at structural mechanics department. It includes creel extruder CHP 32×25, impregnating head, winding device. Cold box and (or) IR heater can be installed between the impregnation device and the coiler to provide the desired temperature distribution along the length of the tape. The coiler allows to wind the tape on the rotating and progressively moving arbor.

Conditions for complete impregnation in impregnation head, formation of sufficient polymer layer to be impregnated and consolidation of individual layers of tape on arbor are set by corresponding dependences between force F and pulling speed (peripheral speed winding) v:

$$F(v) = \mu \cdot R_p \cdot b \cdot h^{1+n} \cdot \left[(1+s) \cdot K_e \cdot \alpha \cdot \frac{R_p}{v} \right]^{-n}; \quad (1)$$

$$F(v) = \frac{\mu \cdot (2h_p \cdot R_p - h_p)^{0,5n} \cdot (s+2)^n \cdot b^{n+2} \cdot v^n \cdot R_p^{1-n}}{(n+2) \cdot h_p^{2n+1}}; \quad (2)$$

$$F(v) = R \cdot b \cdot K_c^n \cdot v^n \cdot \left[\int_0^{x^*(v)} \frac{dx}{\mu(x,v)} \right]^{-1}, \quad (3)$$

where μ – consistency index; R_p – the radius of the cylindrical elements, on which the impregnation occurs; b – width, which glassroving decomposes; h – thickness of the impregnated layer; n – exponent in the law of melt flow; $s = 1 / n$; K_e – effective permeability coefficient of the fibrous layer; α – wrap angle; h_p – thickness of the polymeric layer; R – radius of the arbor; K_c – dimensionless criterion of consolidation; x^* – length of the contact layers of tape on which the temperature is higher than the melting temperature of the matrix polymer.

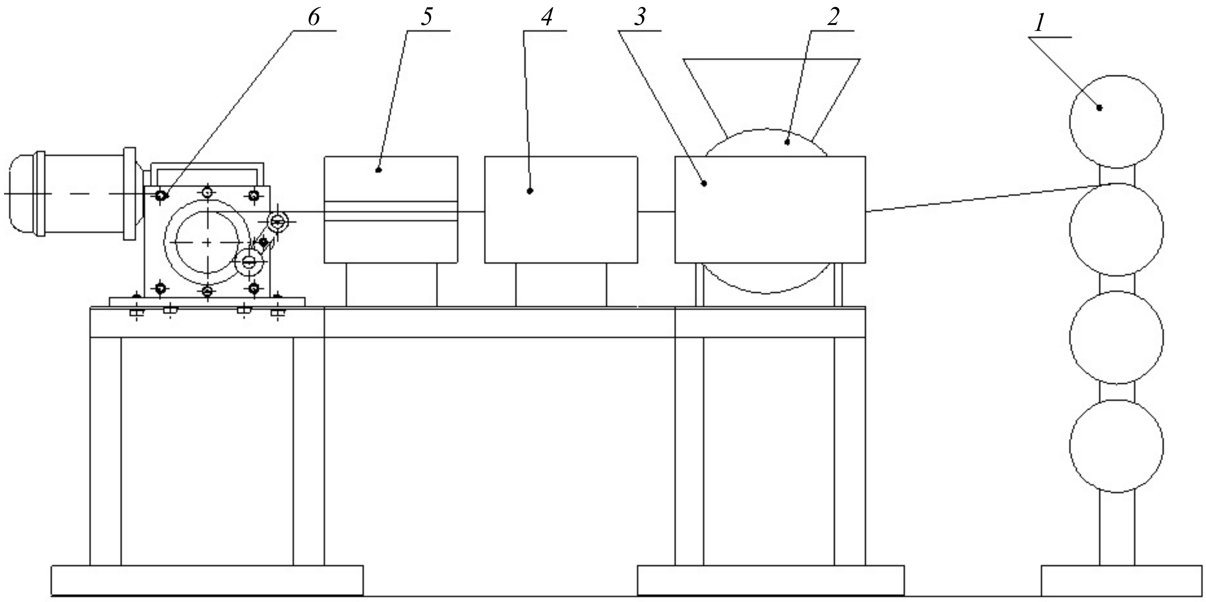

Fig. 1. Scheme of technological line for winding cylindrical and curved products:
1 – creel; *2* – extruder; *3* – impregnator head; *4* – cold box; *5* – IR heater; *6* – coiler

Parameters of the power law flow μ and *n* were determined by capillary method. Temperature dependence of the consistency is set in the form of Arrhenius law:

$$\mu(T) = \mu_0 \cdot \exp\left[\frac{E}{R \cdot T}\right], \qquad (4)$$

where μ_0 – parameter of the law; E – activation energy of viscous flow; R – universal gas constant; T – thermodynamic temperature.

Using relation (4) and the parameters $\mu_0 = 2.9 \cdot 10^{-4}$ Pa · s^n, $E = 63.9$ kJ / (mol · K), the coefficient of consistency in the equations (1)–(3) was determined.

Dimensionless criterion of consolidation was determined by the percolation model [2], specifying the degree of consolidation at least 0.95 ($K_c = 4 \cdot 10^4$).

The temperature in zones of extruder (260–290°C), impregnating head (290°C) was set below the temperature of thermal oxidative degradation of the polymer matrix. The distance between the impregnating head and the point of contact with the tape surface of the arbor was set to the lowest possible for the construction of the coiler (0.2 m).

"Process window" – the system of lines in the coordinates $F - v$, limiting the range of parameters satisfying the requirements of its individual steps was calculated in terms of the technological properties of the material involved in the equations (1)–(3) (Fig. 2). Inside the "window" provided satisfactory quality of products is provided for all three criteria discussed above.

Fig. 2 shows that, for the winding process it is possible to reach quite high productivity. Winding speeds up to about 80 mm / s the main criterion limiting parameters of the winding process, is the criterion of consolidation and at speeds greater than 80 mm / s – the criterion of impregnation of the fibrous layer.

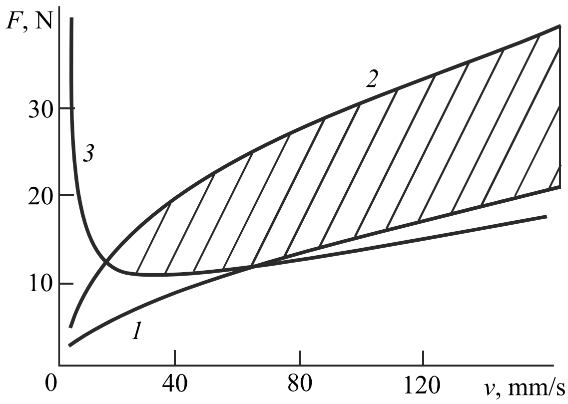

Fig. 2. The parameters boundaries of the peripheral layer winding on thermoplastic cylindrical preform with the following criteria:
1 – impregnation; *2* – forming of sufficient polymer layer; *3* – consolidation

When the winding speed is 56 mm / s and the tension force is about 20 N in the "process window" (see Fig. 2), a product of satisfactory quality is obtained by impregnation and consolidation criteria. The coil pitch was set to (10 ± 1) mm.

The obtained product is shown in Fig. 3. Outside surface further was stitched with grooved roller. Pressing force (10 ± 2) N. Free (outer) surface has irregularities commensurable with the characteristic dimensions (layer thickness) of filler.

Ring-shaped samples (20 ± 2) mm wide were cut and pull-tested. Form of fracture of the sample shows that there is a fairly strong bond between the preform and the tape, as the destruction of the reinforcing layer occured but not its unwinding. Fracture stress in the tape amounted to 180 MPa, which corresponds to the strength of the tape with a given degree of reinforcement.

Fig. 3. Cylindrical product layout

With this technology, curved rods in the form of cramps were also received. In this case winding was carried out immediately after the continuous impregnation of the reinforcing filler. When used this coiler allowing winding with a constant speed of tape handling from impregnating head and using constant tensioning due to the epicyclic gearing. The process parameters and the circuit are almost identical to the winding cylindrical items. i.e. the “process window” in Fig. 2 is also valid for the winding of oval products. By the regimes similar for cylindrical products, oval products in the form of clamps 20 mm wide, 200 mm long were wound. Fig. 4 shows general view of the obtained product.

The resulting oval products were tested for tension. The tests for tension didn’t show layer unwinding which demonstrate good layer consolidation. The destruction occurred in the crest. The maximum tensions in the working part at the destruction point are to 230 MPa, and the maximum tensions in the crest are to 320 MPa.

Fig. 4. Layouts of oval wound products

Conclusion. The one-stage process of winding cylindrical and curved products from recycled polyethylene terephthalate was studied, i.e. the fundamentals are elaborated, regularities are analyzed and the parameters are estimated. The technique of estimating the parameters of the winding process by impregnation and consolidation criteria is elaborated. The technique developed can be used to determine the optimal mode of winding cylindrical and curved products by reinforced tape based on thermoplastic binders.

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