Experimental Determination of Residual Stresses in Wound Unidirectional Glass-Reinforced Plastics

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The residual stresses in prestressed ring-shaped systems of wound unidirectional glass-reinforced tape have been investigated experimentally. The relation between the residual stress and the winding force has been established. A decrease in the specified prestress is demonstrated. The results of tensile tests on free rings of wound glass-reinforced tape are presented.

Oriented glass–reinforced plastics (GRP) are now being widely used to obtain systems with a given prestress. Such systems have proved particularly valuable in electrical machine building, where they are used for traction motor bands, end windings, and other parts of electric motors [1–3]. Oriented GRP in the form of glass-reinforced tape are used for winding. These are essentially anisotropic materials whose properties depend on the fabrication parameters—temperature $t^\circ$, time $\tau$, and pressure $p_0$ [4]. Note that in winding the role of pressure is played by the tension applied to the tape. Therefore the process of winding and subsequent polymerization of the part is accompanied by a change in the initially specified tension [5]. The initial tension diminishes due both to deformation in the radial direction of the wound layers of tape, as a result of the essential anisotropy, and to the softening and subsequent hardening of the resin in the process of polymerization.

Naturally, the development of a winding technology presupposes the rational choice of a tensioning force that would guarantee the obtaining of a structure with a given prestress. Consequently, to make possible the rational design of prestressed structures and to create a corresponding fabrication technology it is necessary to study the forces operating at all stages of the winding process and to establish the relation between the residual stress in the finished part and the initial specified prestress and, in order to estimate the strength of a prestressed structure, the relation between strength and prestress.

This paper reports the results of an experimental investigation of the effect of the prestress on the residual stresses in a ring of unidirectional GRP wound onto a compliant mandrel. The turns were applied in one layer (with respect to height) and their number remained constant. Naturally, the number of turns has an important influence on the loss of prestress, especially in the winding stage, owing to the essential anisotropy of the material. The effect of the number of turns on the residual stresses will be given separate consideration. The structural shape selected for the experiments, a ring, is one of the most convenient for study. At the same time, parts of this shape are in widespread use.

The ring-shaped part was wound on thin-walled metal dynamometer ring or mandrel, with the following dimensions: outside diameter of ring 295 mm, width 100 mm, thickness 4 mm. The dynamometer ring was mounted in a special assembly (Fig. 1) that ensured an elastic support with the transmission of torque from a lathe drive. The glass-reinforced tape was tensioned with a tensioning device, the construction of which is illustrated in Fig. 1. As starting material we used LSB–F unidirectional glass-reinforced tape based on PE–933 resin from the Papers and Cardboards Laboratory of the Lenin Electrical Engineering Institute (this tape is recommended by the laboratory for wound systems and is used in a number of electric machine factories for making prestressed parts). The construction of the wound ring was as follows: number of turns $n = 20$; turns applied in one layer under constant tension.

As the basic parameter, in relation to which the loss of prestress was considered, we took the average normal (along the glass fibers) stress $\sigma_t$. This facilitates the analysis and generalization of the results. It is easy to calculate if one knows the tensioning force. The stresses in the wound part are determined by measuring the circumferential deformation of the metal mandrel on which the part is wound. The deformation of the mandrel was measured with four heat-resistant probes arranged symmetrically around the circumference of the ring at equal distances from its end faces.

During winding the end of the tape is attached to the mandrel. The specified tension was achieved during application of the first turn. During subsequent winding the tension was kept within \( \pm 10\% \) of the specified value. After application of the specified number of turns, a section of tape belonging to the last turn was bonded to the previous turns by the brief application of heat and pressure. The conditions of attachment of the end of the tape after winding (if one uses LSB–F tape that has been stored for not more than six months since fabrication) do not affect the residual stresses. After attachment of the last turn the prestress was recorded and the dynamometer ring with the GRP ring would onto it was placed in a temperature-controlled chamber for polymerization of the resin at an elevated temperature. The polymerization temperature for LSB–F tape, 155° C, was specified by the laboratory. The duration of the polymerization process was
partially determined by the change in relative deformation of the ring. Heating was interrupted when the readings of the strain-gauge system became stabilized, but not before three hours. The composite mandrel-part system was cooled to room temperature.

Fig. 1. Device of winding GRP rings: 1) dynamometer ring, 2) drum, 3) braking disc.

In an experimental study of the process of ring fabrication, the relative deformation of the mandrel was measured throughout the process of fabrication of the part. In order to determine its strength characteristics, the finished part was removed from the dynamometer ring with a special device. After removal of the part, its strength characteristics were determined immediately, since after a certain time a ring of prestressed glass-reinforced tape easily loses stability from the plane of symmetry. In determining their strength characteristics the rings were loaded to destruction.

A typical diagram of the variation of the relative circumferential strain of a dynamometer ring wound with unidirectional glass-reinforced tape is shown in Fig. 2. It reflects the winding process and the processes associated with polymerization of the resin. The curves $\Delta$ (Fig. 2) show the change in relative circumferential strain at four points of the ring, the curve $T$ shows the change in ambient temperature. As may be seen from Fig. 2, the relative strain reaches a maximum at the end of the winding process, at point b. After the specified number of turns has been wound and the end secured (point b), the relative strain is observed to diminish. This trend ceases as polymerization proceeds (segment c–d), but on the segment d–e it recommences, though only because with decrease in temperature the difference in the coefficients of linear expansion of the materials (metal GRP) begins to play a part. At constant temperature after cooling (segment e–f) the relative strain does not change. For the example illustrated in Fig. 2 the winding stress $\sigma_l = 2000$ kgf/cm².

Figure 3 gives the stresses in the GRP ring as a function of the winding stress of the three main stages of fabrication of wound rings. The notation is as follows: $\sigma_{\text{max}}$—maximum stress in wound ring (point b, Fig. 2), $\sigma_{\text{resT}}$—residual stress in GRP ring at end of polymerization at elevated temperature (steady readings), $\sigma_{\text{part}}$—residual stress in finished part at ordinary temperatures after cooling (point e, Fig. 2).

In Fig. 3 the points denote the average values of the quantity determined, calculated by the method of statistical reduction of empirical results for a small sampling of the random variable. In the same figure the broken lines denote the boundaries of the confidence intervals. In processing the results we assumed a normal law of distribution of the random variable, since a qualitative check showed that the distribution of the random variables is only slightly different from a normal one.

As was to be expected, with increase in $\sigma_l$ (Fig. 3) the absolute value of the residual stress in the part also increases. The relation $\sigma_{\text{res}} - \sigma_l$ was investigated in the following range of tape stresses: $1100$ kgf/cm² $< \sigma_l < 4200$ kgf/cm². At $\sigma_l < 1100$ kgf/cm² the residual dual stresses lay within the limits of the permissible measuring error. At $\sigma_l > 4200$ kgf/cm² winding was difficult since the tape was damaged on the drums of the winding mechanism and tended to split along the fibers.

To obtain a clearer picture of the loss of stress we employed relative values. Thus, Fig. 4 gives the variation of the relative quantities $\sigma_{\text{max}}/\sigma_l$, $\sigma_{\text{resT}}/\sigma_l$, and $\sigma_{\text{part}}/\sigma_l$ as a function of the stress in the wound tape. With increase in the tape stress the relative value of the residual stress also increases.

The entire process of loss of prestress can be divided into three main stages: 1) losses during the winding process itself, 2) during the resin polymerization process, 3) during cooling of the wound part and mandrel.

Fig. 2. Variation of strain of dynamometer ring during fabrication of prestressed GRP ring at $\sigma_l = 2000$ kgf/cm².

1. There is an important loss of prestress during the winding stage, the reason being the anisotropy of