GLASS FIBRES AND MATERIALS MADE FROM THEM

MECHANISMS OF BREAKDOWN OF THE STRUCTURE OF GLASS CLOTH DURING IMPREGNATION WITH POLYMER BINDERS

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The basic sources of worsening of the quality indexes of insulating glass cloth and the requirements for the properties of the cloth and binder during impregnation were determined: short pile, gas inclusions, thermodynamic characteristics of binder and monofilament on the binder—monofilament, binder—air, and air—monofilament interface, internal stresses in the structure of the cloth, weave geometry, and position of monofilaments in the complex fibre.

A large number of defects appears in the final stage of fabrication of glass fibre so that up to 40% of product is converted to a lower grade or discarded.

Electron and light microscopic studies of the defectiveness of the structure of translucent varnished glass cloth allow not only investigating the surface defects but also perturbation of the structure in any region.

The defined thickness and breakdown voltage are the most important indexes of the quality of varnished glass cloth. Projecting pile coated by the binder and uneven impregnation have the greatest effect on fluctuations of the thickness. The breakdown voltage basically decreases due to gas bubbles which cannot go out onto the surface of the material during impregnation and polymerization. The breakdown voltage of air is many times lower than for varnished glass cloth. For this reason, gas inclusions practically decrease the thickness of the varnished cloth, preventing electrical discharge on the thickness of the gas bubble. This factor is especially important for thin insulating glass cloth 25-180 \( \mu \)m thick. The internal stresses which arise due to uneven tension and many other factors cause premature breakdown of the structure of varnished glass cloth.

Identification and separation of quality-reducing factors by groups in fractographic analysis reveals the correct technological measures which increase product quality and eliminate these drawbacks.

Observations of the varnished glass cloth surface under a microscope showed that the surface of samples is covered with small cavities from burst gas bubbles arising after impregnation with air. Air bubbles rising to the surface in the polymerization stage burst, creating large cavities.

The filaments (monofilaments) which protrude on varnished glass cloth surface in the form of long piles are pressed to fabric by surface forces of the liquid binder in initial drying and polymerization. Further drying and polymerization fixes the initial position of the monofilament relative the surface of the fabric. Adhesion of protruding short ends of the monofilaments oriented perpendicular to the cloth surface during impregnation is impeded for many of the reasons described below.

Straightening of the monofilament prevents surface forces of the liquid binder from acting. Separation of monofilament from the cloth surface is accompanied by appearance of transverse forces continuously distributed over the length of the monofilament which prevent its separation. The magnitude of these forces is proportional to sag in this section. The proportionality factor is a function of the reaction energy of the monofilament with the cloth surface coated with liquid binder. The specific attractive force of a monofilament raised to height \( y \) over the plane of cloth coated with a binder film is equal to [1]:

\[
 f_0 = Ky, \tag{1}
\]

where \( K = \sqrt{2\sigma \rho g} = 2\sigma \rho /a \) is the dependence between raising height \( y \) and slope \( O \) to horizontal surface of the liquid; \( a \) is the capillary constant.

Equation (1) shows that the force of compression of the monofilament to the surface of the cloth is proportional to the lateral separation of the monofilament. For typical binders and lubricants, a specific monofilament attractive force of 10-50 mN/m corresponds to lateral separation of the monofilament up to 1 mm. The thin liquid film on the surface of the cloth creates a capillary type of bond in the interfibre spaces and compacts the protruding strands and ends of the fibres.

Short ends of protruding monofilaments, for example, fluff "worked" into the cloth during weaving, are the most dangerous. These rigid (on bending) segments of the monofilament cannot be pressed to the surface of the cloth by the surface forces of the liquid film, since their short length for a comparatively small specific attractive force per unit of monofilament length does not exceed the bending energy required for pressing the fibres to the cloth. Meniscus-like nubs can form around such short fibres. If there are many broken and protruding monofilaments, they can form relatively bulky drop-like bulges which increase the total thickness of the complex fibre. Monofilaments tangled in tufts have a bulky deformed structure. The resistance of the crooked monofilaments to compression by surface tension is high. The tuft slightly deformed by the forces of surface tension retains the bulky structure and retains binder cured inside the layer, forming defects of the nub type and drop-like bulges due to the forces of wetting.

Foreign mechanical inclusions deposited from the technological equipment during impregnation and polymerization are also observed on the surface of varnished glass cloth.

Gas inclusions in the form of air bubbles are most frequently observed on the surface and in the bulk of varnished glass cloth. Air inclusions sharply decrease (to 2 kV/mm versus 30 kV/mm) the breakdown voltage of insulating varnished glass cloth (proportional to a decrease in the thickness of the impregnated part of the cloth due to exclusion of the volume of the gas inclusions).

The basic causes of formation of gas bubbles during impregnation of fibre materials are due to the presence of blind and quasi-blind pores, appearance of effects of kinetic nonwetting and mechanical capture of gas in immersion of the material in liquid.

Visual analysis (microscopic study) of the geometric dimensions and interfibre and surface pore profile showed that blind pores are only formed on the surface of complex glass fibres in the form of cracks and are no more than 0.1 μm deep. Interfibre through pores are filled with liquid during impregnation, and the air is totally displaced. However, they can also play the role of quasi-blind pores in which air is retained. In impregnation with viscous liquids, air bubbles are held in complex fibres and cloth with through pores when the material is immersed in liquid at a rate higher than the rate of movement of the liquid in the intrapore space of the immersed material.

In satisfaction of Poiseuille's law, the rate of capillary impregnation is equal to

$$\frac{dl}{dt} = \frac{\sigma \rho r \cos \theta}{2\eta h}.$$

where $\eta$ is the viscosity of the liquid; $r$ is the effective radius of the pore space; $h$ is the length of the filled part of the capillary.

It follows from Eq. (2) that retention of gas bubbles during impregnation decreases with a decrease in the contact angle of wetting, viscosity of the liquid, and an increase in the surface tension of the liquid.

The studies of kinetic wetting in [2] show that an effect of kinetic nonwetting of the moving cloth, where the dynamic contact angle of wetting attains $\theta = \pi/2$ or higher, appears for high speeds at the initial time of contact of the material with the liquid or for high immersion speeds. Deposition of the liquid is accompanied by an effect of tightening of the air space in this case. In these conditions, the entrained air space prevents contact with the liquid in individual sections.

In immersion of fibre material in a liquid, a conical surface [3] of displaced gas space is formed inside the material and its instability can cause trapping of gases. Observations show that air can also be mechanically trapped by large interfilament spaces in the cloth, especially in impregnation of thick and multilayer structures.

The example of layer-by-layer examination of a group of gas bubbles is very graphic. If the surface of a bubble is considered to be independently positioned in the binder, then the tips of upright monofilaments in bubbles are visible in a deeper cut, indicating that the tips of the monofilaments are pronounced bubble concentrators in the structure of varnished glass cloth and correspondingly elements that prevent migration of bubbles to the surface.

In examining the distribution of gas bubbles on the level of woven fibres in varnished cloth, note that larger bubbles, as concentrators of groups of bubbles, are more frequently located on the fibre or in overlaps of warp and weft threads. Marginal bubbles of smaller size or intermediate between the bubbles located on the fibres are primarily positioned in the spaces between filaments filled with binder. This obviously indicates that the surface of monofilaments in the complex fibre is the basic zone of bubble formation and retention.