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THERMAL EXPANSION OF COMPONENTS OF FILM ELECTRIC HEATERS

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The thermal expansion coefficients of components of film electric heaters over the temperature range 20-450°C are measured.

A film electric heater (FEH) has a complex multilayer structure incorporating different components, including a heat-conducting and simultaneously load-carrying part - a substrate. The lifetime of FEH operation is mainly governed by reliability, thermal stability, and adhesive strength (of an insulating layer) and by the electrical insulation of a resistive film from a metal substrate. The electrical insulation is a glass enamel coating (film).

Among many factors exerting an influence on the onset and magnitude of a thermal stresses that are able to destroy an FEH structure the difference in the thermal expansion coefficient values of the insulating layer and the substrate is the most important. Here, the thermal stresses arise in the electrical insulation at different values of the thermal expansion coefficients (TECs) of it and the substrate even when a temperature drop is absent.

The appearance of stresses above the allowable values results in a gradual destruction of the FEH layers and shortening of the operating life or in failure altogether, due to electric breakdown of the deformed electrical insulating layer.

The thermal cyclicity of operation of the FEH and all its components under on/off conditions over a wide temperature range aggravates the problem of durability and increased operating life. Having regard for the fact that the internal FEH structure is sufficiently miniaturized and none of its components can undergo current repairs in practice, the materials of which they are constructed must be systematically and comprehensively studied over a broad temperature range. First, this is true for the study of the TEC of the materials of the components, knowledge of which is necessary to provide efficiency of operation of the FEH structure and not just an extended operating life. Moreover, knowledge of the TEC of materials is needed to make FEH designs. These measurements are of independent methodical value, related to making corrections for thermal expansion when other thermophysical properties of materials are studied experimentally.

Determining a phase change temperature by the use of dilatometry substantially supplements thermal analysis and sometimes is a more reliable and plausible procedure for its measurement.

Thermal expansion studies are also concerned with obtaining additional information on the physical phenomena of ordering and decomposition of solid solutions, recrystallization, phase changes, softening temperature, etc. [1]. Such information is required, for example, to establish the temperature limits of reliable operation of an FEH and its components, process temperatures, etc.

The TEC of a metal substrate fabricated from rimming steel 08KP, cover-coat enamel ESP-117, ground-coat enamel ESG-21, and electroinsulating glass SE is measured by the automatic-control quartz dilatometer DKV-5A. This instrument provides automatic-control recording of dilatometric curves over the temperature range 20 to 900°C. For small displacements to be measured the instrument is equipped with the mechanically controlled tube 6MKh5S, possessing high sensitivity and a strictly linear characteristic. The measuring method is differential and relative, with the use of quartz glass as a comparison measure for thermal expansion. The instrument operation is based on measuring the length change difference between a test sample and the structural components of a dilatometer measuring cell - support pipe 5 and pusher 2 (Fig. 1).

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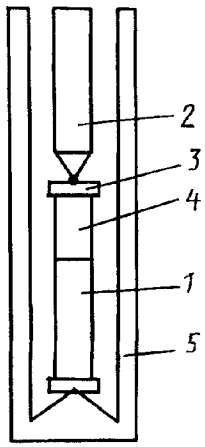

Fig. 1. Schematic diagram of the measuring cell of a differential quartz dilatometer: 1) test sample; 2) quartz pusher rod; 3) quartz plate; 4) quartz insert; 5) quartz support pipe.

Sample 1, manufactured by cooking [2-5], whose ends are nonparallel by no more than $\pm 20\,\mu$m, is fastened between two quartz plates 3 having cone-shaped recesses. The quartz pusher cone is machined to fit in the recess of the top plate, while the cone of the quartz support pipe is seated against the recess of the bottom plate. Cone-shaped junctions prevent bending forces from being exerted on the pusher. They provide a small contact surface between the sample and the measuring cell components. The latter substantially decrease heat exchange between them by heat conduction and decrease the distortion of the sample temperature field, which is important for accurate TEC measurements.

The quartz pusher is connected via an adapter with a spring head spindle suspended by two thin membrane springs. The springs afford the system mobility in the longitudinal direction and rigidity in the transverse one.

The automatic-control dilatometer is equipped with a two-coordinate plotting recording potentiometer of the type PDP 4-002. The input signal from the mechanically controlled tube, proportional to the sample length change, is applied to one of the axes (Y) of the potentiometer. The sample temperature is measured by a Chromel-Alumel thermocouple, whose thermo e.m.f. is applied via a voltage divider to the other axis (X) of the potentiometer. The electromechanical unit for automatic-control heating and cooling of the sample at a given rate consists of a capacitor-start engine of the type RD-09, a friction clutch, and the electric circuits of a slide wire, triac, and trinistor.

Experimentally obtained temperature dependences of a sample as a function of time at different heating rates show that during the initial heating stage up to 150°C the temperature grows very slowly ($\sim$ 0.015 K/sec) under all operating conditions. This must be maintained to obtain a valid dilatogram and, hence, a reliable value of the TEC. Furthermore, over the starting section the TEC value to be determined is greatly affected by the correction for the dilatometer zero drift, whose accurate and reliable determination is provided by the low heating rate of the samples itself.

For any differential method the calculation formula, from which the TEC is determined, has the following form:

$$\alpha = \alpha_s + \alpha_q ,$$

where α is the mean value of the TEC of the test sample, K^{-1}; α_s is the TEC of the sample, taking into account the correction for the zero drift alone, K^{-1}; α_q is the quartz glass TEC. Let us give this formula in final form in terms of quantities determined beforehand and measured by the dilatometer DKV-5A:

$$\alpha = \frac{\Delta l_n - \Delta l_z}{l_0} \frac{1}{t_{i+1} - t_i} + \alpha_q ,$$

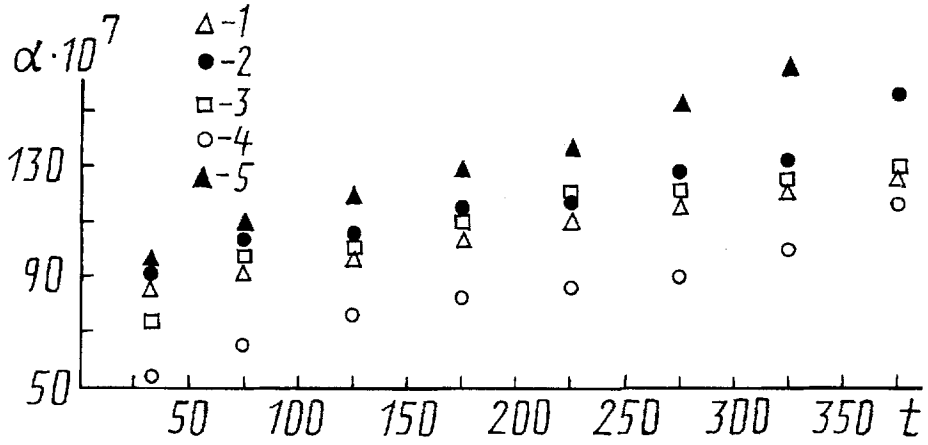

Fig. 2. Experimental data for the temperature dependence of the TEC of test samples: 1) titanium film; 2) glass SE-105; 3) borosilicate glass ESG-21; 4) borosilicate glass ESP-117; 5) steel 08KP. α, K^{-1}; t, °C.

Here l_0 is the sample length at the initial temperature t = 20°C; l_n is the test sample length change over the temperature range $t_{i+1} - t_i$, determined from the dilatogram as the difference of successive potentiometer readings at the indicated temperatures; l_z is the length change of the reference quartz sample and the measuring cell over the temperature range $t_{i+1} - t_i$, mm (the instrument zero drift is determined beforehand over the indicated temperature range in special experiments).

The obtained value of the TEC relates to the mean temperature:

$$t_m = \frac{t_{i+1} + t_i}{2}.$$

Based on these formulas and the recommendations of [6, 7], we obtain a calculation formula for the relative error of the measured values of the TEC:

$$\frac{\delta\alpha}{\alpha} = \frac{\delta(\alpha_s + \alpha_q)}{\alpha_s + \alpha_q}.$$

The numerical value of the error is no more than ± 3% at a reliability of 0.95.

From the results for the temperature dependence of the TEC of steel, glass, and glass enamel samples over the temperature range 20-450°C the following conclusions (Fig. 2) may be made:

1. Comparison of the experimentally obtained values of the TEC for steel samples with the available data [8] shows that these correlate reasonably well. This points to reliability of the operation of the dilatometer and the performed calibration of the zero drift over the entire temperature range.

2. The studies also show that over the entire temperature range 20-450°C the values of the TEC of a steel sample are somewhat higher than those of glass and glass enamel samples. The maximum disparity between the TEC values is observed for a cover-coat glass enamel and a steel sample (approx. imataly 1.5 timea) for temperatures from 400 to 450 °C.

3. In the cover-coat enamel layer, when the FEH is heated, there arise tensile stresses that are large compared to the other layers over the entire temperature range. In manufacturing an FEH, it is necessary to strictly meet the sequence of operations and the process parameters that guarantee a certain structure of the FEH components and their reliability in operation.

4. The following analytical relations for the TEC of steel, glass, and glass enamel samples are obtained over the temperature range 20-450°C [8]: for steel 08KP $\alpha \cdot 10^6 = 9.67 + 1.9 \cdot 10^{-2}$t, for cover-coat enamel ESP-117 $\alpha \cdot 10^6 = 5.146 + 0.019$ t; for ground-coat enamel ESG-21 $\alpha \cdot 10^6 = 4.644 + 6.7 \cdot 10^{-2}$ t; for glass SE-105 $\alpha \cdot 10^6 = 8.219 + 2.45 \cdot 10^{-2}$ t. These equations can be recommended for heat-engineering calculations.

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