THERMAL PREPARATION OF A HETEROGENEOUS LIGHT-SENSITIVE MEDIUM

WITH COMPACT MAGNETIC FILLER PACKING, FOR OPTICAL IMAGE RECORDING

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Heating a heterogeneous light-sensitive medium with compact packing of the magnetic core to the premelting temperature of the binder is considered; a method is obtained to realize stabilization of such a system.

The process of optical image formation on a light-sensitive heterogeneous medium (HM) with compact packing of the magnetic filler, created in the Institute of Radio Engineering and Electronics (IRE) of the Academy of Sciences of the USSR [1], is of great interest.

The light-sensitive medium under investigation is a sandwich plate (Fig. 1) consisting of a HM layer with compact filler packing (the binder is paraffin, the filler is 1-μm size ferric oxide Fe_3O_4 particles) 1; a layer of pure paraffin 2; a Lavsan substrate 3. In the solid-state paraffin is a molecular polycrystal consisting of a mixture of solid limit hydrocarbons C_nH_{2n+2} [2]. Because of the inhomogeneous composition of the paraffin, the width of the solid-state—liquid phase transition is a quantity on the order of 10°C [2]. Because of the singularities of the binder phase transition, the medium is heated to a premelting temperature (to the temperature of the beginning of the phase transition) in the first stage of the preparation to record. In the second stage the paraffin softens and melts and goes from a structure with compact packing of a HM in crystalline paraffin over to a structure with noncompact packing of the HM particles in a paraffin melt ("friable structure"). The recording process consists of shaping the image (guided coagulation of the particles in the paraffin melt) and fixing it (crystallizing the paraffin).

The first stage is examined of the process of preparing the HM with compact magnetic filler packing for recording (without taking account of the phase transition), which is accomplished as follows. Initially, the light-sensitive medium on the substrate side is set into contact with a thermostate. Consequently, the plate is heated uniformly to the temperature of the thermostat (such a method does not yield high accuracy of heating to the premelting temperature but is used as the initial heat). Then the forward surface of the film $x = 0$ (layer 1 in Fig. 1) is heated by a constant intensity light pulse Q_0 of duration t_d

$$Q = \begin{cases} Q_0, & 0 \leqslant t \leqslant t_d, \\ 0, & t > t_d. \end{cases} \tag{1}$$

The thin paraffin film is optically transparent in the visible and IR ranges [1], consequently it is considered that the light pulse is absorbed completely by the first layer of HM particles with the compact packing because of the compact particle packing.

To solve the problem formulated above it is necessary:

1) To determine the parameters of the preparation pulse (the relationship between the intensity and the duration) at which the system is ready for structural changes (the passage to the "friable structure") up to the pulse termination, i.e., the temperature at the boundary $x = x_1$ reaches the premelting temperature. It is here necessary that the first layer be heated uniformly and melting not be started;

2) To set the time interval during which the system is ready for the next recording and to set the possibility for temperature stabilization in such a system.

3) To clarify the role of the substrate, i.e., to determine how the temperature pulse is propagated over such a sandwich structure, what percentage of the energy communicated by the

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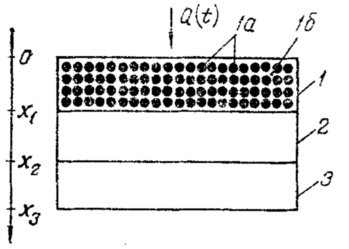

Fig. 1. Light-sensitive HM with compact magnetic filler packing: 1) layer of HM with compact filler packing; 1a) filler (particles); 1b) binder (paraffin); 2) layer of pure paraffin; 3) transparent lavsan (dacron) substrate; 0, x_1, x_2, x_3 are coordinates of the layer boundaries, and Q(t) is the preparatory light pulse.

system at a given time is absorbed in this layer, and what is the percentage of the heat loss to the environment.

The following assumptions were made in solving the problem: the temperature field is one-dimensional, the physical parameters in the problem are independent of the temperature, the porosity of the MH with compact particle packing is m = 0.3, where the HM with compact particle packing is considered a homogeneous layer with equivalent heat conduction [3]

$$K_1 = K_m(4m/[1 + K_p/K_m]) + K_p(1 - 2m) \tag{2}$$

The density and specific heat of the equivalent medium are [4]:

$$\rho_1 = \rho_p(1 - m) + \rho_m m, \quad c_1 = c_p(1 - m) + c_m m \tag{3}$$

It is moreover assumed that the conditions of ideal thermal contact hold between the layers, a constant temperature (contact with the thermostat) is maintained on the boundary between the third layer and the environment $x = x_3$, and the initial plate temperature equals the thermostat temperature. And finally, we consider that a thermal flux governed by (1) is given on the boundary x = 0 because of the total absorption of the light pulse by the first layer of particles of the domain of the HM with compact packing (see Fig. 1).

In this case the desired problem reduces to the following system of equations:

$$\begin{gathered}
\frac{\partial T_i}{\partial t} = \varkappa_i \frac{\partial^2 T_i}{\partial x^2} \quad (i = 1,\ 2,\ 3), \\
x = 0 \quad -K_1 \frac{\partial T_1}{\partial x} = Q(t), \\
x = x_1 \quad -K_1 \frac{\partial T_1}{\partial x} = -K_2 \frac{\partial T_2}{\partial x}, \quad T_1 = T_2, \\
x = x_2 \quad -K_2 \frac{\partial T_2}{\partial x} = -K_3 \frac{\partial T_3}{\partial x}, \quad T_2 = T_3, \\
x = x_3 \quad T_3 = T_0, \\
t = 0 \quad T_i(x,\ 0) = T_0.
\end{gathered} \tag{4}$$

The following constraint is imposed on the pulse duration

$$t > 0 \quad T_i \leqslant T_f. \tag{5}$$

We introduce the dimensionless quantitites

$$\begin{gathered}
\xi = x/l,\ \tau = \varkappa_1 t/l^2,\ u_i = (T_i - T_0)/(T_f - T_0), \\
\varkappa_{21} = \varkappa_2/\varkappa_1,\ \varkappa_{31} = \varkappa_3/\varkappa_1,\ K_{21} = K_2/K_1,\ K_{32} = K_3/K_2, \\
\overline{Q} = Ql/K_1\Delta T,\ \Delta T = T_f - T_0.
\end{gathered} \tag{6}$$

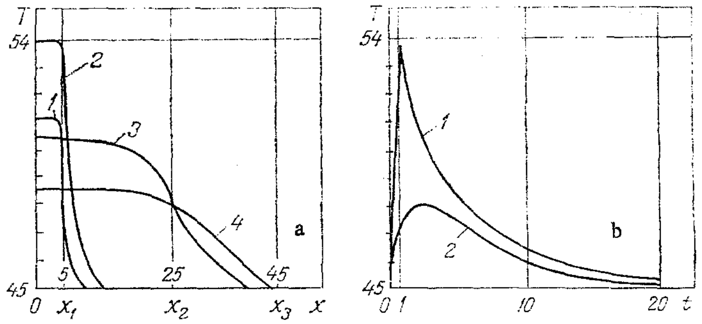

Fig. 2. Temperature change T(x, t) in a sandwich structure (heating pulse intensity $Q = 50\ W/cm^2$, duration $t_d = 0.46$ msec, initial temperature $T_0 = 45°C$, x is the coordinate, t is the time): a) depending on the coordinate for different times (1) t = 0.2 msec; 2) 0.46; 3) 2; 4) 4); b) depending on the time on the layer boundaries (1) $x = x_1$ is the boundary between the first and second layers; 2) $x = x_2$ is the boundary between the second and third layers), x, μm.

The system (4) in the dimensionless quantities (6) becomes

$$\frac{\partial u_1}{\partial \tau} = \frac{\partial^2 u_1}{\partial \xi^2} \quad (0 < \xi < \xi_1),$$
$$\frac{\partial u_2}{\partial \tau} = \varkappa_{21} \frac{\partial^2 u_2}{\partial \xi^2} \quad (\xi_1 < \xi < \xi_2).$$
$$\frac{\partial u_3}{\partial \tau} = \varkappa_{31} \frac{\partial^2 u_3}{\partial \xi^2} \quad (\xi_2 < \xi < 1). \tag{7}$$
$$\xi = 0 \quad \bar{Q} = -\frac{\partial u_1}{\partial \xi},$$

$$\xi = \xi_1 \quad \frac{\partial u_1}{\partial \xi} = K_{21} \frac{\partial u_2}{\partial \xi}, \quad u_1 = u_2,$$
$$\xi = \xi_2 \quad \frac{\partial u_2}{\partial \xi} = K_{32} \frac{\partial u_3}{\partial \xi}, \quad u_2 = u_3, \tag{8}$$
$$\xi = 1 \quad u_3 = 0,$$
$$\tau = 0 \quad u_i = 0,$$
$$\tau > 0 \quad u_i \leqslant 1.$$

In such a formulation, the problem was solved numerically by finite differences. The implicit Frank–Nicholson scheme was used [5]. The computation was on an ES-1033 computer for the following values of the layer parameters (see Table 1): the thermal flux varied between 2 and 500 W/cm^2, the initial temperature T_0 between 48 and 25°C, the premelting temperature of paraffin was $T_{pm} = 54°C$, and the layer thicknesses were $l_1 = 5$ μm, $l_2 = 20$ μm, $l_3 = 20$ μm.

The temperature distribution T(x, t) in the sandwich structure was found as a function of the time and coordinates for the mentioned values of the parameters Q and T_0 as a result of the computations. Typical curves for such a structure are represented in Fig. 2a for different times ($Q = 50\ W/cm^2$, $t_d = 0.46$ msec, $T_0 = 45°C$). It was clarified that the first layer can be considered uniformly heated to 0.1°C accuracy for intensities $Q < 200\ W/cm^2$ (which corresponds to $t_d \geqslant 0.1$ msec). An estimate for the limit value of the heating pulse intensity can be obtained from the stationary solution. In this case the temperature varies linearly. We shall consider the layer heated uniformly if the temperature difference at the layer ends does not exceed 1°C: $|\Delta T| < 1°C$. It follows from (4) that $|\Delta T/l| = Q/K_1$ from which the estimate for the intensity is $Q < (K_1)/(l_1)1°$, which corresponds to $Q = 200\ W/cm^2$ for the parameters under consideration $K_1 = 10^{-1}\ W/cm \cdot °C$ and $l_1 = 5 \cdot 10^{-4}$ cm.

TABLE 1. Thermophysical Properties of the Materials Used

Material	Heat conduction K, W/cm·°C	Specific heat c, J/g·°C	Density ρ, g/cm³	Thermal diffusivity ϰ, cm/C
Fe_3O_4	10^{-1}	0,6	5	$3{,}3\cdot 10^{-2}$
Paraffin	$2\cdot 10^{-3}$	1,4	0,9	$2\cdot 10^{-3}$
Lavsan	$2{,}3\cdot 10^{-3}$	1,05	1,2	$1{,}8\cdot 10^{-3}$

Time dependences of the temperature change on the layer boundaries $x = x_1$ and $x = x_2$ were obtained for the optimal band of heating pulse intensity values (see Fig. 2b). It was clarified that an abrupt diminution in the temperature started from the instant of heating pulse termination, and the temperature on the boundary of the first layer drops 2°C between 0.5 and 2 msec for the mentioned intensity range ($Q < 200$ W/cm²).

A graph was obtained of the dependence of the heating pulse duration needed on its intensity, for which the temperature on the surface $x = x_1$ reached a given quantity (Fig. 3) up to the time of pulse termination. The dependence of t_d on $\bar{Q}$ is shown in Fig. 3, where $\bar{Q}$ is shown in Fig. 3, where $\bar{Q}$ varies between $2.81\cdot 10^{-2}$ and 3.05, which in dimensional variables corresponds to a Q between 3 and 200 W/cm² and a T_0 between 25 and 48°C. It is seen from the graph presented that for definite values of Q for each T_0 (see Table 2), a limit intensity Q_{lim} exists for which the system leaves the stationary heating mode with a limit temperature equal to T_f. The accuracy of 0.1°C of obtaining the given temperature is reached in a time on the order of 50 msec. For Q less than Q_{lim} the system emerges into the stationary mode with a temperature less than T_f, i.e., a minimal limit intensity corresponds to each T_f, permitting the realization of the first stage in preparing the system to record. Emergence on the asymptote Q_{lim} occurs here with high accuracy: for a 2% heating pulse intensity deviation from Q_{lim} the ultimately achievable temperature changes by ±0.2°C. The dependence obtained permits selection of the heating pulse working parameters. Moreover, the presence of a stationary regime affords a possibility of solving the problem of temperature stabilization of such a system. Since problems of minimizing the energy expenditure in preparation does not occur during the preparation of the system to record, then continuous heating, which assures a stationary regime, permits realization of system preparation and maintenance in readiness to record an unlimited time.

The existence of a limit stationary regime also follows from the analytical solution for the system under consideration, which is obtained under the following assumptions: 1) the domain of heating pulse intensity $Q < 200$ W/cm², i.e., the first layer is considered heated uniformly and a boundary condition of the type "contact with an ideal conductor" is considered on the boundary $x = x_1$ in place of the first layer; 2) since the thermal and mechanical characteristics of paraffin and lavsan are similar (see Table 1 and Fig. 2a), then the second and third layers are considered as one layer with a total thickness of $l = l_2 + l_3$ and average thermal parameters, i.e., a plate is investigated, one of whose surface ($x = 0$) is abutting on the layer of an ideal conductor, while the other ($x = l$) is maintained at a constant temperature. This problem reduces to the following system of equations

$$\begin{gathered} \frac{\partial T}{\partial t} = \varkappa \frac{\partial^2 T}{\partial x^2}, \\ x = 0 \quad -K\frac{\partial T}{\partial x} + \rho_1 c_1 l_1 \frac{\partial T}{\partial t} = Q, \\ x = l \quad T = T_0, \quad t = 0 \quad T(x,\ 0) = T_0. \end{gathered} \tag{9}$$

The solution of (9) is presented in [6]

$$T = T_0 + \frac{Ql}{K}\left\{\frac{l-x}{l} - \sum_{n=1}^{\infty} \frac{2h\exp(-\varkappa\alpha_n^2 t)\sin\alpha_n(l-x)}{l\alpha_n\cos\alpha_n l\{l(\alpha_n^2+h^2)+h\}}\right\}; \tag{10}$$

here $h = \rho c/\rho_1 c_1 l_1$ while α is a root of the equation $\alpha \operatorname{tg} \alpha h = h$.

It follows from an analysis of (10) that for $t > 100$ msec the system emerges into the stationary regime with a given temperature $T = T_f$ for $x = 0$ if $Q = (T_k - T_0)K/l$, which

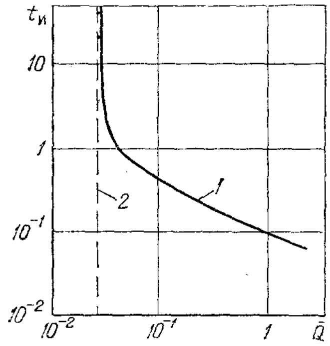

Fig. 3

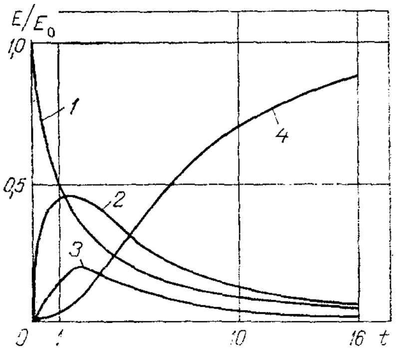

Fig. 4

Fig. 3. Dependence of the heating pulse duration needed t_d (1) on its intensity $\bar{Q}$. The asymptote is $\bar{Q}_{lim} = 2.81 \cdot 10^{-2}$ (2).

Fig. 4. Distribution of the energy E referred to the total energy E_0 communicated to the system up to the given time, over the layers as a function of the time t and the energetic losses in the environment: 1) first layer; 2) second; 3) third; 4) losses; heating pulse intensity Q = 50 W/cm^2, and duration t_d = 0.46 msec.

TABLE 2. Dependence of the Limit Light Pulse Intensity Q_{lim} on the Initial System Temperature T_0

T_0, °C	25	30	35	40	45	48
Q_{lim}, W/cm^2	15,1	12,5	9,92	7,31	4,71	3,03

corresponds to Q = 4.5 W/cm^2 for the parameters of the system under study (T_f = 54°C, T_0 = 45°C, K = $2 \cdot 10^{-3}$ W/cm·°C, l = 40 μm). This value of Q is in good agreement with the quantity obtained by the numerical solution of the system (6): Q = 4.7 W/cm^2.

Let us consider the heat balance in the system under investigation (Fig. 4). It is seen that during a time on the order of 1-2 msec the first layer loses 50% of the energy communicated to it. The heat elimination to the thermostat plays a substantial part. For heating pulses of duration from 10-10^{-2} msec 50% of the communicated energy leaves to the thermostat in a time of 5-10 msec, and 90% of the energy in the time 16-20 msec. For heating pulses of duration $t_d \geq 10$ msec noticeable heat losses to the thermostat start during the action of the pulse. In this case 50% of the energy goes to the thermostat in 15-20 msec, and 90% in 40 msec, where all the energy communicated to the plate leaves for the thermostat in the case of the stationary regime described above.

Therefore, the first stage in the process of preparing a HM layer with compact particle packing for optical image recording is examined in operation. An allowable intensity working interval is established in the utilization of which uniform heating of the NH with compact particle packing is realized to a binder premelting temperature (paraffin). Furthermore, a dependence is obtained for the heating pulse duration on the intensity needed for heating to a given temperature, and the time interval is determined during which the system is readied for the next recording under pulse heating. A method is obtained for realizing the stabilization of such a system with sufficiently high accuracy. And, finally, graphs are constructed for the time dependence of the distribution of the energy communicated to the system over the layers, as are graphs of the energetic losses, and the times are determined during which the energy communicated to the system goes into the environment.

NOTATION

Q, heating pulse intensity, W/cm^2; t, time, msec; t_d, heating pulse duration, msec; x, coordinate, μm; K_i, heat-conduction coefficient of the i-th layer, W/cm·°C; m, porosity; ρ_i, density of the i-th layer, g/cm^3; c_i, specific heat of the i-th layer, J/g·°C; $\varkappa_i$, thermal diffusivity coefficient of the i-th layer, cm^2/sec; T_i, temperature of the i-th layer, °C; T_0, thermostat temperature, °C; T_f, paraffin premelting temperature, °C; l_i, thickness of the i-th layer, μm; l, thickness of the whole film, μm; ξ, a dimensionless coordinate; τ, dimensionless time; u_i, dimensionless temperature; $\bar{Q}$, dimensionless heat flux; Q_{lim}, limit heating pulse intensity for which the system emerges into the stationary temperature regime, W/cm^2; K, heat-conduction coefficient of the total paraffin and Lavsan layer, W/cm^2; $\varkappa$, thermal diffusivity coefficient of the total paraffin and Lavsan layer, cm^2/sec; l, total thickness of the layers of paraffin and the substrate, cm. Subscripts i = 1 corresponds to the first layer $[0, x_1]$; i = 2 to the second layer $[x_1, x_2]$; i = 3 to the third layer $[x_2, x_3]$; p, for particles; and m for the paraffin medium.

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HEAT FORMATION IN A VISCOELASTIC RECTANGULAR PRISM UNDER FORCED HARMONIC OSCILLATIONS

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The heat formation in a viscoelastic harmonically excited prism that occurs because of mechanical energy dissipation is investigated.

The extensive application of viscoelastic materials in modern engineering arouses considerable interest in the investigation of the thermomechanical behavior of viscoelastic bodies. These materials possess low heat conductivity, a capacity to dissipate mechanical energy, and a temperature dependence of the physicomechanical and strength characteristics. Interaction of the strain and temperature fields is manifested most clearly under continued harmonic deformation. A substantial rise in temperature of the oscillating body is possible here, which occurs because of mechanical energy dissipation. According to some experimental results [1-3], even in the quasistatic frequency domain the heating can influence the longevity of structural elements decisively under definite conditions. In the dynamic frequency range, the level of heat formation rises significantly in the neighborhood of resonances, and it acquires a still more important role [4, 5].

On the basis of the exact solution of the plane dynamic problem of viscoelasticity obtained in [6], heat formation in a viscoelastic prism subjected to harmonic excitation is investigated in this paper. The complex viscoelastic shear modulus is considered frequency-dependent and temperature-independent. An infinitely long prism of rectangular section $|\xi| \leq L$, $|\eta| \leq H$ is considered, which performs forced harmonic tension–compression oscillations under the action of a normal load applied to two opposite faces $\eta = \pm H$. Harmonic displacements with amplitude $u_0 = L\alpha_0$ are given on these faces in solving the dynamics problem [6]. Convective heat transfer is realized between the prism faces and the environment of

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