FLASH IR DRYING OF ELECTRICAL PORCELAIN AT VARIOUS PRESSURES

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It is shown that a satisfactory approximation can be given for the observed results on flash IR drying of bonded powders; a criterion characteristic of the process is derived. The results allow prediction of drying processes.

IR radiation penetrates to depths of 0.05–1 mm into a moist bonded porcelain powder in accordance with the structure; any further inward heat transfer is governed by the thermophysical properties of the material. The outer layer dries rapidly, and the pores shrink, which impairs liquid and vapor transport; continued supply of heat may produce pressure gradients that disrupt the material. The drying mechanism must be known for flash heating in order to produce high-grade components.

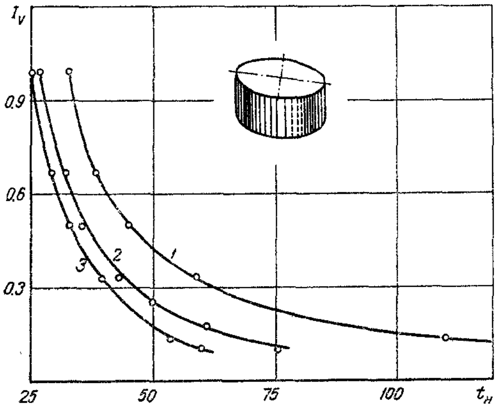

Fig. 1. Relation of t_H (min) to I_V for $I_L = 5$ sec and pressures p_m (Torr) of: 1) 720, 2) 195, 3) 50.

Preliminary tests showed that the present method is best used at high radiation fluxes ($E > 1$ W/cm^2). Moist porcelain compositions absorb well in the long-wave IR, so we used sources with emission maxima at about 2.7 μm.

Drying at reduced pressure means that the vapor pressure within the material is lower, which provides more rapid water removal at lower temperatures. In this case, diffusion is accentuated by increase in T and by reduction in p_m. The material is especially liable to crack in the initial period of drying, so it is important to provide the optimum conditions at this stage, and hence we have used the maximum drying rate $(dX/dt)^*$ as a basic concept in conjunction with t_H [1], the time needed to evaporate half of the water. However, the over-all performance in drying can be evaluated only by carrying the process to completion.

Experimental. It was found that I_L did not influence the drying at 720, 195, or 50 torr for $I_V = 1$. With $E = 1.4$ W/cm^2, however, the quality of the product is much improved if $I_L < 20$ sec and $I_V < 0.6$; $I_L > 20$ sec and $I_V > 0.6$ caused the internal water transport to be less than the external mass transfer, with the result that the surface dried out rapidly and shrank. This leads to relatively rapid migration of the evaporation zone into the material, with production of a large temperature gradient at the surface and retardation of the flow of vapor in the material. The intervals between radiation pulses do not allow the previous mass flux to be regained, which ultimately leads to failure of the specimen.

Here Lu < 1, so it is necessary [2] to control the energy supply carefully. Figure 1 shows the relation of t_H to I_V for $I_L = 5$ sec at several p_m, together with the shape of the specimen (diameter 60 mm, height 25 mm, side and base isolated).

Increase in I_I causes increase in t_H, but reduction in p_m can render this effect negligible. Figure 2 shows that t_H is linearly related to the mean pressure p_m, while Fig. 3 shows $I_V = f[(dX/dt)^*]$. The linear region represents continuous heat and mass transfer within the material. A notable point is that I_V can then be reduced substantially; but t_H then increases, so the maximum I_V must be as close as possible to the limit of cracking. For instance, if we take $I_V > 0.65$, the marked increase in temperature gradient produces a large mass flux g_X opposed to the mass flux g_M caused by the moisture gradient, and this retards the over-all mass transfer. The mass flux increases with the evaporation rate until the walls of the pores are disrupted; the required transport rate cannot be obtained under such conditions, and the straight line in Fig. 3 gives way to a curve that tends asymptotically to a limiting drying rate.

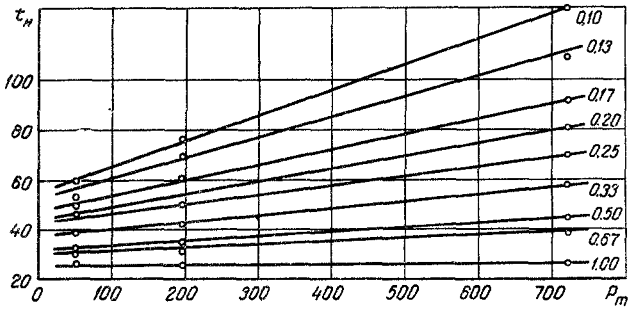

Fig. 2. Relation of t_H (min) to p_m (Torr) for various I_V (stated on curves at $E = 1.4$ W/cm^2.

This effect occurs the more rapidly the higher E and I_V and the lower the mass-transfer coefficients. If the drying is properly arranged, the IR energy is used only in continuous evaporation. The properties of the material must be such as to provide maximal water transfer during I_L; the danger of cracking de-

Concepts and Definitions Used in Flash IR Drying

Concept	Symbol	Dimensions	Definition
Pulse length	I_L	sec	Irradiation time
Interval between pulses	I_I	sec	Time during which material is not irradiated
Pulse ratio	I_V	—	I_L/I_I
Pulse frequency	I_f	$\sec^{-1}$	$I_f=\frac{1}{I_L+I_I}$ or $I_f=\frac{I_V}{I_L(I_V+1)}$
Pulse amplitude	I_G	W/cm^2	Corresponds to the radiation flux density E
Total duration of irradiation	t_B	min	Total duration of pulses in drying time t
Total length of pauses in irradiation	t_P	min	Total length of all intervals between pulses in drying time t

creases as the diffusion coefficient and thermal conductivity increase. Moreover, the energy required in continuous mass transfer increases with p; reduction from 720 to 50 torr at $I_V = 0.5$ represents about 25% saving of energy, and even larger savings are possible if I_V is reduced. Flash IR drying therefore gives better results under vacuum than at atmospheric pressure.

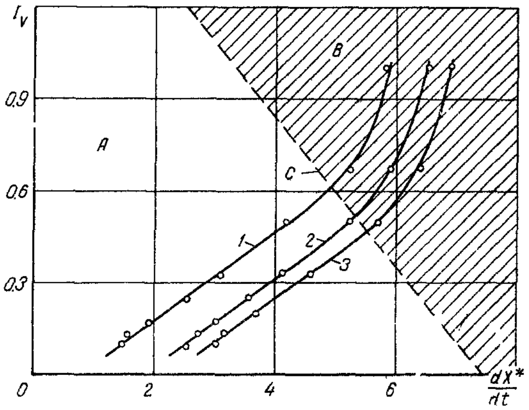

Fig. 3. Relation of $I_V = f[(dX/dt)^*]$ to p_m for E = 1.4 W/cm²; A) region of continuous migration, B) cracking region, C) limit of formation of cracks for p_m (torr) of: 1) 720, 2) 195, 3) 50. The units for $(dX/dt)^*$ are g/kg-min · 10^{-3}.

The reason for this is that mass transfer encounters better conditions as p is reduced, since the internal resistance is lower, because the temperature gradient is reduced and with it the water flux due to thermal water transfer. A single straight line represents $(dX/dt)^* = f(t_H)$ in logarithmic coordinates for the various p_m, since for any t_H there is only one $(dX/dt)^*$, which is dependent only on the characteristic water content. On the other hand, a plot of $(dX/dt)^*$ against t_B involves the pulse parameters, p_m, and the size of the material.

Laws of IR Drying. The test data show that $I_V = f(t_H)$ (Fig. 1) is of the same form for all p_m, and the curves are approximated closely by

$$I_V = C_1/t_H^B \tag{1}$$

or

$$t_H = \sqrt[B]{C_1/I_V}. \tag{2}$$

Then B can be deduced graphically; it is a function of p_m alone, which takes the form

$$B = \xi - \varkappa \lg p_m \tag{3}$$

or, numerically,

$$B = 4.175 - 0.925 \lg p_m. \tag{3a}$$

The B deduced graphically from Fig. 1 are $B_{720} = 1.54$, $B_{195} = 2.07$, $B_{50} = 2.62$, while those found by calculation from (3a) are $B_{720} = 1.53$, $B_{195} = 2.06$, $B_{50} = 2.60$.

C_1 may be calculated from (1) via known I_V and t_H. We use the arithmetic mean of the values corresponding to different I_V at fixed p_m, the results for 720, 195, and 50 torr being respectively 182.22, 833.19, and 4689.44 (C_1 for 50 torr nearly 25 times that for 720 torr). This illustrates the marked effect of p_m on the drying. However, the form of $C_1 = f(p_m)$ is also dependent on the shape of the specimen.

The relation of $(dX/dt)^*$ to t_H is

$$\left(\frac{dX}{dt}\right)^* = C_2/t_H \tag{4}$$

or

$$C_2 = \left(\frac{dX}{dt}\right)^* t_H. \tag{4a}$$

C_2 for the region of constant drying rate is 0.185, which is the arithmetic mean of the values for the various p_m.

Then (2) and (4) allow one to derive the drying characteristics of porcelain in the first period of drying under pulse irradiation. For instance, the maximum drying rate for a given I_V is

$$\left(\frac{dX}{dt}\right)^* = C_2/\sqrt[B]{C_1/I_V}. \tag{5}$$

If it is not necessary to know the absolute magnitudes of $(dX/dt)^*$ and t_B, we can use the ratio of these in graphical constructions, the empirical coefficients then becoming dimensionless.

These relationships do not define the optimum drying conditions, which have to be based on special studies taking into account the structure, the modes of heat and water transport, and the way in which the water is bound to the material.

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