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THICKNESS OF THE LAYER OF SORPTION DEVELOPER IN CAPILLARY INSPECTION

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The article introduces and analyzes expressions for determining the thickness of the layer of developer applied to the inspected solid body for revealing surface flaws of different shape by methods of capillary flaw detection.

Various methods of capillary inspection (or capillary flaw detection) are classed in one group by the following traits. Firstly, they are all intended for revealing surface flaws. Secondly, their principle of functioning is based on the use of a luminescent or colored indicator liquid (penetrant) which, having been previously applied to the inspected surface and then removed from it, penetrates from flaws into the thin layer of powdery or suspension developer and forms on its surface a contrasting, visualized "trace" of the flaw. A recent theoretical investigation of the hydrodynamics of indicator liquids in processes of capillary flaw detection made it possible to construct a hydrodynamic theory of the stages of making flaws visible and to derive a number of formulas for evaluating the sensitivity threshold and the duration of inspection [1, 2]. It follows from the obtained results that in revealing blind surface flaws with the aid of a powdery sorption developer, there exists a maximal thickness of the layer of developer h_{max}, and when this is exceeded, flaws of a certain width of opening (or less) cannot be made visible any more. We will find the values of h_{max} in revealing cracks with plane parallel and nonparallel walls, and also of cylindrical flaws.

Crack with plane parallel walls (Fig. 1a). If on an inspected solid surface there are flaws, then an indicator liquid applied to it penetrates into their cavities under the effect of capillary pressure $p_c = 2\sigma \cos \theta/H$. As a rule, the penetrants wet solid surfaces well, and therefore for the sake of simplicity of further explanation we put $\cos \theta \simeq 1$. After the liquid has been removed from the surface, the residual depth to which it fills the crack with depth l_0 and width H is determined by the expression $l = n l_0 \psi$ $(0 < n \leq 1)$ [1], where $\psi = 2\sigma/(2\sigma + p_a H)$. Assume that to the inspected surface a layer of powdery sorption developer with thickness h is applied (Fig. 1a). The penetrant from the cavity of the flaw wets the developer, and as a result a "trace" of the flaw forms on the outer surface of the developer which becomes luminescent in ultraviolet light. In dependence on the ratio between the

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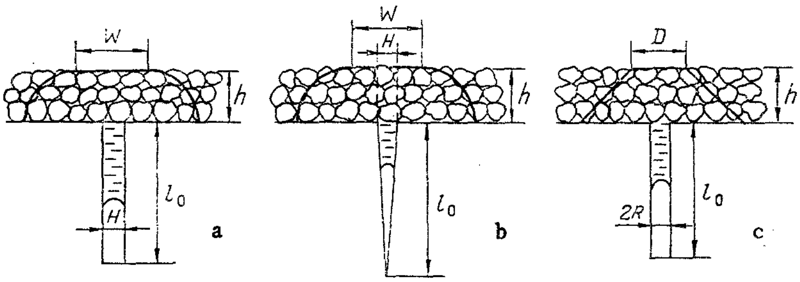

Fig. 1. Absorption of the indicator liquid from a flaw by the layer of powdery sorption developer: a) crack with plane parallel walls; b) crack with plane nonparallel walls; c) cylindrical flaw.

dimensions R_e and H we have to examine different conditions of the penetrant being extracted by the developer from the cavity of the flaw.

In case $R_e < H$, the penetrant is extracted completely from the flaw and its entire volume impregnates a strip of the layer of developer forming a "trace" of the crack. We will take it that the surface of the front of penetrant migrating in the developer is part of the lateral surface of a cylinder with radius h. We denote by W the minimal width of the strip of the outer surface of the layer of developer impregnated by the penetrant at which a flaw can be made visible. Then the thickness of the layer of developer has to satisfy the inequality

$$Hnl_0\psi \geqslant \left(Wh + \frac{\pi h^2}{2}\right)\Pi, \tag{1}$$

from which follows the expression for the maximal thickness of the layer h_{max} at which the flaw can be made visible:

$$h_{\max} = -\frac{W}{\pi} + \sqrt{\left(\frac{W}{\pi}\right)^2 + \frac{2nl_0\psi H}{\pi\Pi}}. \tag{2}$$

When the inspected surface is covered with a layer of developer whose thickness $h > h_{max}$, then on its outer surface above the mouth of the crack with depth l_0 and width H an impregnated layer forms whose width is smaller than W. As a result the flaw is not revealed, no matter how long the process of inspection lasts.

Figure 2a shows the dependence of h_{max} on the width of opening of the detected flaws with their specified depth and n = 0.9 calculated by formula (2). It can be seen, e.g., that with the mentioned characteristics of the penetrant and the developer, when $R_e < H$, flaws with depth $l_0 = 2 \cdot 10^{-3}$ m and width $H = 10^{-5}$ m are revealed when the thickness of the layer of developer $h < 1.9 \cdot 10^{-5}$ m. An analysis of formula (2) shows that with the mentioned values of the magnitudes it contains, $h_{max} < 2.022 \cdot 10^{-5}$ m for any H.

In case $R_e > H$ not all the penetrant is absorbed by the developer from the cavity of the flaw, and there remains the minimal residual depth [1]:

$$l_{\min} = l_0 \frac{2\sigma(R_e - H)}{p_a R_e H + 2\sigma(R_e - H)} = \frac{\psi l_0 (R_e - H)}{R_e - \psi H}. \tag{3}$$

Consquently in that case the thickness of the layer of developer has to satisfy the inequality

$$Hnl_0\psi - \frac{l_0\psi(R_e - H)}{R_e - \psi H} H \geqslant \left(Wh + \frac{\pi h^2}{2}\right)\Pi,$$

from which we can easily derive the formula for calculating h_{max}:

$$h_{\max} = -\frac{W}{\pi} + \sqrt{\left(\frac{W}{\pi}\right)^2 + \frac{2Hl_0\psi}{\pi\Pi}\left(n - \frac{R_e - H}{R_e - \psi H}\right)}. \tag{4}$$

It can be seen from this formula that when $R_e > H$ and in the process of removing the indicator liquid from the inspected surface the depth to which it fills the flaw decreased to such a value that

$$n < \frac{R_e - H}{R_e - \psi H}, \tag{5}$$

then the flaw is not detected, no matter what the thickness of the layer of developer h is. From this inequality we can easily obtain an expression for the minimal width of the crack

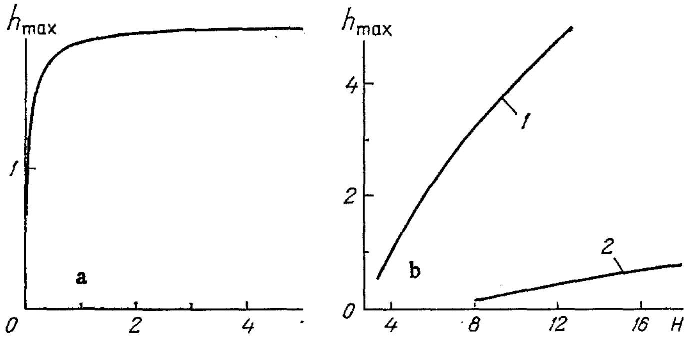

Fig. 2. Dependence of the maximal thickness of the layer of developer h_{max} on the width of the crack with plane parallel walls H for the cases $R_e < H$ (a) and $R_e > H$ (b) with $\sigma = 3.7 \cdot 10^{-2}$ N/m, $W = 10^{-4}$ m, $p_a = 10^5$ N/m, n = 0.9; a) $l_0 = 2 \cdot 10^{-3}$ m, $\Pi = 0.5$ (h_{max}; H, 10^{-5} m); b) $l_0 = 10^{-2}$ m, $\Pi = 0.4$, $R_e = 2 \cdot 10^{-5}$ m (1); $l_0 = 2 \cdot 10^{-3}$ m, $\Pi = 0.4$, $R_e = 5 \cdot 10^{-5}$ m (2). h_{max}, 10^{-5} m; H, 10^{-6} m.

revealed with residual depth of its filling nl_∞ with developer with effective pore radius R_e:

$$H_{min} = \frac{(1-n)(p_a R_e - 2\sigma)}{2p_a} + \sqrt{\left[\frac{(1-n)(p_a R_e - 2\sigma)}{2p_a}\right]^2 + \frac{2(1-n)\sigma R_e}{p_a}}. \tag{6}$$

Below we present the values of H_{min} calculated by formula (6) for $R_e = 5 \cdot 10^{-6}$ m, $\sigma = 3.7 \cdot 10^{-2}$ N/m, $p_a = 10^5$ N/m², and different n:

n	0,95	0,9	0,85	0,8	0,75	0,7	0,65	0,6	0,55	0,5
H_{min}, 10^{-6}m	0,55	0,86	1,13	1,39	1,63	1,87	2,11	2,34	2,57	2,79

Figure 2b shows the curves $h_{max} = h_{max}(H)$ plotted according to formula (4). The separate sections of the curves correspond to the thicknesses of the layer of developer $h < R_e$, which is possible with such a wetting of particles of developer by the penetrant when $D_p < R_e$. However, since $R_{po} < D_p/2$, and the penetrant usually wets the particles of developer well, the case $h < R_e$ is rarely encountered in practice. Other conditions being equal, h_{max} increases with increasing n and l_0 and with decreasing R_e.

Thus, for detecting flaws with plane parallel walls the thickness of the layer of developer applied to the inspected surface must not exceed the value

$$h_{max} = -\frac{W}{\pi} + \begin{cases} \sqrt{\left(\frac{W}{\pi}\right)^2 + \frac{2nl_0\psi H}{\pi\Pi}}, & R_e < H, \\ \sqrt{\left(\frac{W}{\pi}\right)^2 + \frac{2l_0\psi H}{\pi\Pi}\left(n - \frac{R_e - H}{R_e - \psi H}\right)}, & R_e > H. \end{cases}$$

Cracks with Plane Nonparallel Walls (Fig. 1b). First we determine the maximal depth of filling of such a crack with penetrant l_∞. We denote by p_c^{max} the maximal capillary pressure corresponding to the position of the meniscus of penetrant at the depth l_∞, and by p_{cm}^{max} the maximal pressure of the air compressed in the channel. Then

$$p_c^{max} = \frac{2\sigma l_0}{H(l_0 - l_\infty)}, \tag{7}$$

and from the Boyle–Mariotte equation

$$p_a l_0 H = p_{cm}^{max}(l_0 - l_\infty) H_0, \tag{8}$$

where H_0 is the width of the crack at the depth l_∞. Since $H_0 = (l_0 - l_\infty)H/l_0$, and $p_{cm}^{max} = p_c^{max} + p_a$, we obtain from formulas (7) and (8) the expression

$$\frac{2\sigma l_0}{H(l_0 - l_\infty)} + p_a = \frac{p_a l_0^2}{(l_0 - l_\infty)^2}$$

which we rewrite in the form

$$l_\infty^2 - \frac{2l_0(\sigma + p_a H)}{p_a H} l_\infty + \frac{2\sigma l_0^2}{p_a H} = 0. \tag{9}$$

The solution of Eq. (9) leads to the following expression for the maximal depth of penetration of the penetrant into the crack, regardless of the dissolution and diffusion of the gas:

$$l_\infty = l_0 \left[1 + \frac{\sigma}{p_a H} - \sqrt{1 + \left(\frac{\sigma}{p_a H} \right)^2} \right]. \tag{10}$$

As a result of removal of the penetrant from the inspected surface the residual depth to which it fills the crack cavity is $l_1 = n l_\infty$, where $0 < n \leqq 1$. Extraction of the penetrant from the flaw by a layer of sorption developer with thickness h, applied to the inspected surface, is in this case described by the following equations:

$$-\frac{dl}{dt} = \frac{H^2 (l_0 - l)^2}{12 l_0^2 \mu l} \left[\frac{p_a l_0^2}{(l_0 - l)^2} - \frac{2\sigma l_0}{H (l_0 - l)} - p_1 \right], \tag{11}$$

$$\frac{dy}{dt} = \frac{k}{\mu y} \left(p_1 - p_a + \frac{2\sigma}{R_e} \right). \tag{12}$$

Here, Eq. (11) corresponds to the flow in the crack cavity, and (12) corresponds to the migration of the penetrant front in the layer of developer along the inspected surface. The condition of conservation of the mass of penetrant has the form

$$\frac{H + H\frac{l_0 - n l_\infty}{l_0}}{2} n l_\infty = \Pi \left(Hh + \frac{\pi h^2}{2} + 2yh \right) + \frac{H + H\frac{l_0 - l}{l_0}}{2} l, \tag{13}$$

from which obtain after simplification:

$$\Pi h \left(H + \frac{\pi h}{2} + 2y \right) = H \left(n l_\infty - l + \frac{l^2 - n^2 l_\infty^2}{2 l_0} \right). \tag{14}$$

It can be seen from Eqs. (11) and (12) that incomplete extraction of penetrant occurs when the following equalities apply:

$$\frac{p_a l_0^2}{(l_0 - l)^2} - \frac{2\sigma l_0}{H (l_0 - l)} - p_1 = 0, \quad p_1 - p_a + \frac{2\sigma}{R_e} = 0,$$

from which it follows that when there is a positive root of the equation

$$l^2 - 2 l_0 \frac{H (p_a R_e - 2\sigma) + \sigma R_e}{H (p_a R_e - 2\sigma)} + l_0^2 \frac{2\sigma (R_e - H)}{H (p_a R_e - 2\sigma)} = 0 \tag{15}$$

the penetrant is extracted from the crack cavity to the depth l_{min} only. Thus, the "trace" of a crack converging on the surface of the layer of developer forms a volume of penetrant in the crack cavity bounded by the depths from $n l_\infty$ to l_{min}.

The solution of Eq. (15) is

$$l_{min} = l_0 \left[1 - \frac{\sigma R_e \pm \sqrt{(\sigma R_e)^2 + (p_a R_e H)^2 - 2 p_a \sigma R_e H^2}}{H (2\sigma - p_a R_e)} \right], \tag{16}$$

but for it to exist, the following conditions have to be fulfilled:

$$(\sigma R_e)^2 + (p_a R_e H)^2 - 2 p_a \sigma R_e H^2 \geqslant 0, \tag{17}$$

$$l_{min} \geqslant 0. \tag{18}$$

When $p_a R_e > 2\sigma$, inequality (17) is always fulfilled, and the solution of inequality (18) leads to the condition

$$H < R_e, \tag{19}$$

whose fulfillment corresponds to incomplete extraction of penetrant from the flaw to the depth

$$l_{min} = l_0 \left[1 + \frac{\sigma R_e - \sqrt{(\sigma R_e)^2 + (p_a R_e H)^2 - 2 p_a \sigma R_e H^2}}{H (p_a R_e - 2\sigma)} \right]. \tag{20}$$

The minus sign in front of the root follows from the condition $l_{min} < l_0$.

More complex is the case $p_a R_e < 2\sigma$. From (17) we obtain the condition

$$H < \frac{\sigma R_e}{\sqrt{p_a R_e (2\sigma - p_a R_e)}}, \tag{21}$$

at which the penetrant is not completely extracted from the crack, and inequality (18) has to be considered in two cases: for $H < \sigma R_e/(2\sigma - p_a R_e)$ and $H > \sigma R_e/(2\sigma - p_a R_e)$. When $H < \sigma R_e/(2\sigma - p_a R_e)$, it follows from (16) and (18), and also from the condition $l_{min} < l_0$, that incomplete extraction of penetrant occurs with condition (19), where the value of l_{min} is determined by expression (20), and complete extraction occurs when $H > R_e$. If $H > \sigma R_e/(2\sigma - p_a R_e)$, it can be shown that in the range

$$\frac{\sigma R_e}{2\sigma - p_a R_e} < H < \frac{\sigma R_e}{\sqrt{p_a R_e (2\sigma - p_a R_e)}} \tag{22}$$

with $R_e < \sigma/p_a$ there may exist two positive roots of Eq. (15) satisfying the solution of (16). However, it follows from physical considerations that in this case only the larger root with the plus sign in expression (16) corresponds to the conditions of the penetrant attaining the minimal equilibrium depth l_{min}. Consequently, if $p_a R_e < 2\sigma$, and at the same time $H < \sigma R_e/(2\sigma - p_a R_e)$, then the penetrant is extracted completely by a given developer from a crack with width $H < R_e$, and to the depth l_{min} determined by expression (20) when the width of opening is $H < R_e$.

When $p_a R_e < 2\sigma$, the penetrant is also extracted incompletely from cracks whose mouth opening H satisfies inequality (22).

With complete extraction of penetrant from the crack the thickness of the layer of developer h has to satisfy the following inequality:

$$n \frac{H\left(1 + \frac{l_0 - n l_\infty}{l_0}\right)}{2} l_\infty \geqslant \left(Wh + \frac{\pi h^2}{2}\right) \Pi.$$

As a result of simple transformations we obtain

$$h^2 + \frac{2W}{\pi} h - \frac{2nHl_\infty}{\pi\Pi} \left(1 - \frac{nl_\infty}{2l_0}\right) \leqslant 0,$$

from which follows the expression for the maximal thickness of the layer of developer at which a visible trace of the flaw forms

$$h_{max} = -\frac{W}{\pi} + \sqrt{\left(\frac{W}{\pi}\right)^2 + \frac{nHl_\infty}{\pi\Pi}\left(2 - \frac{nl_\infty}{l_0}\right)}, \tag{23}$$

where l_∞ is determined by formula (10). This expression applies to the detection of cracks whose mouth opening satisfies the following inequalities:

$$\left.\begin{array}{l} H > R_e \quad \text{for } R_e > \dfrac{2\sigma}{p_a} \quad \text{or for} \quad R_e < \dfrac{2\sigma}{p_a} \text{ and } H < \dfrac{\sigma R_e}{2\sigma - p_a R_e}, \\ H > \dfrac{\sigma R_e}{\sqrt{p_a R_e (2\sigma - p_a R_e)}} \quad \text{for} \quad R_e < \dfrac{2\sigma}{p_a} \text{ and } H > \dfrac{\sigma R_e}{2\sigma - p_a R_e}. \end{array}\right\} \tag{24}$$

Figure 3a presents the dependence of h_{max} on the width of the crack mouth opening H when condition (24) is fulfilled.

It follows from the presented curve that when, e.g., a layer of the given developer with thickness $h = 3.6 \cdot 10^{-5}$ m is applied to the inspected surface, cracks with depth $l_0 = 10^{-2}$ m and width of opening $H > 2 \cdot 10^{-6}$ m are made visible.

In case of incomplete extraction of penetrant from the cavity of the flaw it is ensured that the trace is made visible if the following inequality is fulfilled:

$$nl_\infty \frac{H\left(1 + \frac{l_0 - nl_\infty}{l_0}\right)}{2} - l_{min} \frac{H\left(1 + \frac{l_0 - l_{min}}{l_0}\right)}{2} \geqslant \Pi h \left(W + \frac{\pi h}{2}\right),$$

which we change to the form

$$h^2 + \frac{2W}{\pi} h - \frac{2H}{\pi\Pi}\left[nl_\infty\left(1 - \frac{nl_\infty}{2l_0}\right) - l_{min}\left(1 - \frac{l_{min}}{2l_0}\right)\right] \leqslant 0,$$

where the values of l_∞ and l_{min} are determined by expressions (10) and (20), respectively. From this we find the maximal thickness of the layer of developer in case of incomplete extraction of penetrant from the cavity of the flaw

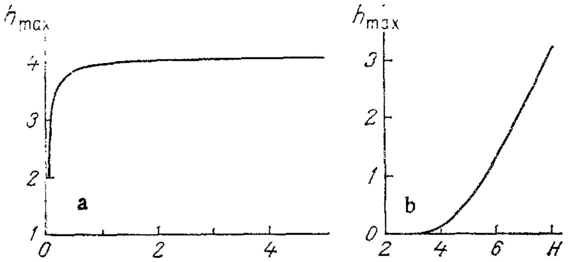

Fig. 3. Dependence of the maximal thickness of the layer of developer h_{max} on the width of opening H of a crack with plane nonparallel walls for the cases $R_e < H$ (a) and $R_e > H$ (b) with $\sigma = 3.7 \cdot 10^{-2}$ N/m, $W = 10^{-4}$ m, $p_a = 10^5$ N/m², n = 0.9: a) $l_0 = 10^{-2}$ m, $\Pi = 0.5$ (h_{max}; H, 10^{-5} m); b) $l_0 = 10^{-3}$ m; $\Pi = 0.4$, $R_e = 10^{-6}$ m. h_{max}, 10^{-6} m; H, 10^{-7} m.

$$h_{\max} = -\frac{W}{\pi} + \sqrt{\left(\frac{W}{\pi}\right)^2 + \frac{H}{\pi\Pi}(nl_\infty - l_{\min})\left(2 - \frac{nl_\infty - l_{\min}}{l_0}\right)}. \tag{25}$$

This expression determines the maximal thickness of the layer of developer in the detection of cracks whose mouth opening has the width

$$\left.\begin{aligned} &H < R_e \text{ for } R_e > \frac{2\sigma}{p_a} \text{ or for } R_e < \frac{2\sigma}{p_a} \text{ and } H < \frac{\sigma R_e}{2\sigma - p_a R_e}, \\ &\frac{\sigma R_e}{2\sigma - p_a R_e} < H < \frac{\sigma R_e}{\sqrt{p_a R_e (2\sigma - p_a R_e)}} \text{ for } R_e < \frac{2\sigma}{p_a} \text{ and } H > \frac{\sigma R_e}{2\sigma - p_a R_e}. \end{aligned}\right\} \tag{26}$$

It follows from expression (25) that the range of values of the number n, corresponding to the residual depth of filling the cavity of the flaw with indicator liquid before the layer of developer is applied to the inspected surface, has to satisfy the inequality

$$n > \frac{l_{\min}}{l_\infty}, \tag{27}$$

where l_∞ and l_{min} are determined by formulas (10) and (16). When $n < l_{min}/l_\infty$, a flaw is not detected.

Figure 3b illustrates the dependence of h_{max} on H with specified properties of the penetrant and developer for $R_e > 2\sigma/p_a$. It can be seen that in our case a layer of developer with thickness $h = 3.3 \cdot 10^{-6}$ m suffices to make visible cracks with depth 10^{-3} m and width of mouth opening $H > 8 \cdot 10^{-7}$ m.

Cylindrical Flaw. Let us examine a layer of powdery sorption developer placed above the mouth of a cylindrical flaw with radius R (see Fig. 1c). For the sake of simplicity of further calculations we will assume that the annular front of the indicator liquid migrating in the developer is part of the lateral surface of a cone whose generatrix is inclined to the base at an angle of 45°. We denote by D the minimal diameter of a "trace" of the cylindrical flaw that is made visible.

In the case under consideration, like in the case of carcks with plane-parallel walls, complete extraction of penetrant by the developer occurs when $R_e < R$, and incomplete extraction to the depth l_{min} when $R_e > R$, where

$$l_{\min} = l_0 \frac{2\sigma(R_e - R)}{p_a R_e R + 2\sigma(R_e - R)}. \tag{28}$$

The volume of penetrant entering the flaw in consequence of capillary impregnation is determined as

$$V_{\max} = \frac{2\pi R^2 n l_0 \sigma}{2\sigma + p_a R} = \pi R^2 n l_0 \psi, \tag{29}$$

where $0 < n \leq 1$ characterizes the residual degree of filling of the flaw with penetrant after the penetrant has been removed from the inspected surface. The minimal volume of penetrant V_{vis} necessary for forming a visible trace of the flaw is found in the following way:

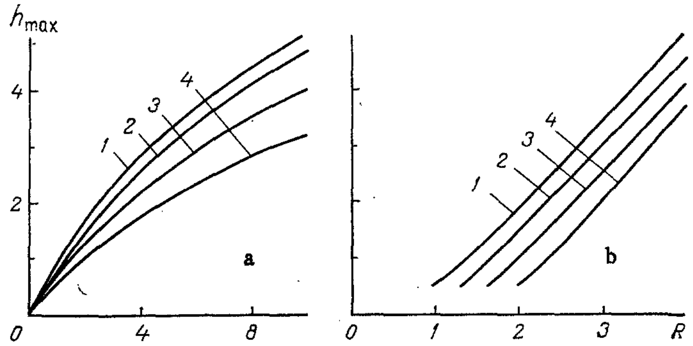

Fig. 4. Dependence of the maximal thickness of the layer of developer h_{max} on the radius of the cylindrical flaw R for the cases $R_e < R$ (a) and $R_e > R$ (b) with $\sigma = 3.7 \cdot 10^{-2}$ N/m, $D = 10^{-4}$, $p_a = 10^5$ N/m², and n = 1 (1), 0.9 (2), 0.8 (3), 0.7 (4): a) $l_0 = 2 \cdot 10^{-3}$ m, $\Pi = 0.5$ (h_{max}, 10^{-5} m; R, 10^{-5} m); b) $l_0 = 5 \cdot 10^{-3}$ m, $\Pi = 0.4$, $R_e = 5 \cdot 10^{-5}$ m. h_{max}, 10^{-5} m; R, 10^{-5} m.

$$V_{vis} = \frac{\pi\left(\frac{D}{2}+h\right)^3}{3} - \frac{\pi\left(\frac{D}{2}\right)^3}{3} = \frac{\pi h}{3}\left(\frac{3D^2}{4} + \frac{3D}{2}h + h^2\right). \tag{30}$$

Using formulas (28)-(30) we can formulate the following inequalities which have to be satisfied by the thickness of the layer of developer if a visible "trace" of a cylindrical flaw is to be obtained on its outer surface:

$$3R^2 n l_0 \psi \geqslant \Pi h\left(\frac{3D^2}{4} + \frac{3Dh}{2} + h^2\right) \quad \text{for } R_e < R$$

and

$$3R^2\left[n l_0 \psi - l_0 \frac{2\sigma(R_e - R)}{p_a R_e R + 2\sigma(R_e - R)}\right] \geqslant \pi h\left(\frac{3D^2}{4} + \frac{3Dh}{2} + h^2\right) \quad \text{for } R_e > R.$$

With specified properties of the flaw detection materials and dimensions of the flaws, we obtain from the above inequalities the expressions for determining the maximally admissible thickness of the layer of developer

$$h_{max} = \left[\left(\frac{D}{2}\right)^3 + \frac{3R^2 n l_0 \psi}{\Pi}\right]^{1/3} - \frac{D}{2} \quad \text{for } R_e < R, \tag{31}$$

$$h_{max} = \left[\left(\frac{D}{2}\right)^3 + \frac{3R^2 l_0 \psi}{\Pi}\left(n - \frac{R_e - R}{R_e - \psi R}\right)\right]^{1/3} - \frac{D}{2},$$

$$n > \frac{R_e - R}{R_e - \psi R} \quad \text{for } R_e > R. \tag{32}$$

It can be seen from the last expression that the number n, characterizing the depth to which the cylindrical flaw is filled with penetrant before powder is applied to the inspected surface, has to satisfy the condition $n < (R_e - R)/(R_e - \psi R)$, and the formula for calculating the minimal radius of the flaw that is detected with the known values of n and R_e coincides with (6).

Figure 4 illustrates the curves $h_{max} = h_{max}(R)$ plotted for different values of n by formulas (31) (Fig. 4a) and (32) (Fig. 4b) with specified values of R_e, l_0, D, Π, σ, and p_a. It can be seen that for detecting cylindrical flaws the layer of powdery developer has to be thinner than in the case of plane cracks. With specified properties of the liquid and of the powder, even with n = 1, for flaws with radius of opening $R = 10^{-5}$ m in case $R_e < R$ the thickness of the layer of developer must not exceed 10^{-5} m, and in case $R_e > R$ it must not exceed $6 \cdot 10^{-6}$ m.

Thus we obtained expressions for determining the maximally admissible thickness of the layer of sorption developer h_{max} in revealing flaws with specified dimensions and with different shapes: a) cracks with plane parallel walls; b) cracks with plane nonparallel walls; c) cylindrical flaws. It was demonstrated that when the width of opening of a flaw is smaller than the effective pore radius R_e, the penetrant is not fully absorbed by the developer, and than there exists a minimal residual depth of filling of the flaw with penetrant characterized by the value of n at which detection of the flaw is possible.

NOTATION

h, thickness of the powder layer; σ and μ, surface tension and coefficient of viscosity of the indicator liquid, respectively; θ and θ_1, contact wetting angle of the inspected surface and of the powder particles, respectively, by the penetrant; H, width of opening of the crack; R, radius of the cylindrical flaw; l_0, depth of the flaw; p_a, atmospheric pressure; R_{po}, mean pore radius of the powder; $R_e = R_{po}/\cos\theta_1$, effective pore radius; D_p, mean particle size of the powder; W, minimal with of the "trace" of a crack made visible; D, minimal diameter of the "trace" of a cylindrical flaw made visible.

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THE ACCURACY CHARACTERISTICS OF A THERMOREFRACTOMETRIC GAS ANALYZER

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Models have been constructed reflecting the dependence of the measurement error on gas analyzer parameters. The effects of each of the factors on the error measurements have been examined.

Recent researches in gas analysis have led to some novel methods based on fundamental results obtained for example in solid-state physics, optics, hydrodynamics, and heat transfer. These include the gradient-refractometric method of analyzing gas mixtures [1].

A thermorefractometric gas analyzer is one form of implementation for this method [2], but an examination of this instrument would be incomplete without an analysis of the accuracy characteristics. Separate analysis of the effects from each of the working parameters on the error of measurement has been based on experiment planning [3]. The instrument is considered as a multiparameter system, whose output (here the error of measurement) is dependent in a random fashion on the input parameters: cell wall temperature, gas mixture flow, temperature gradient in cell walls, cell length, and test component concentration. Most of the input parameters are working ones, i.e., they determine the mode of operation.

Models were constructed from experiment plans of Hartley type for five factors and Box type for four. The gas mixtures were nitrogen + nitrous oxide and nitrogen + carbon dioxide. For the first of these mixtures, experiment gave the following model relating the measurement error to each of the five factors:

$$S_1 = 3{,}6 - 0{,}5x_1 + 0{,}9x_3 + 0{,}5x_4 + 0{,}6x_5 + 0{,}9x_3^2 - 0{,}5x_1x_3 - x_2x_3 - 0{,}5x_1x_4 + x_2x_4 - 0{,}8x_1x_5 + 0{,}5x_4x_5. \quad (1)$$

This shows that the most marked dependence, which is also nonlinear, occurs between the temperature gradient along the cell and the error. More detailed analysis is best based on a graphical representation. We reduce the dimensions by fixing one of the factors such as the cell length at the zero level. We then substitute into the initial model for the values of the third factor at the upper and lower levels and at the central point of the plan, which

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