NEW APPROACH TO THE DESCRIPTION OF DEFECTS DEVELOPMENT AT PENETRANT INSPECTION

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Abstract: The analysis of all basic hydrodynamic and physical-chemical processes underlying defects development at penetrant inspection is proposed for the first time in this paper. It permits to elucidate both a discrepancy between calculated values for duration of developer application stage and the corresponding experimental data and some other discrepancies.

It is established that the process of drawing out of a penetrant from defects by developer's layer is characterized, as a rule, by three basic stages for wet developer and by two stages for dry developer.

For wet developer the first stage corresponds to the interaction of two liquids: a penetrant and liquid phase of a developer. Classical capillary penetration of a penetrant into the developer layer represents the second stage. In the most cases this stage is very short-term (maximum some seconds). The longest-duration stage is the third one. Two processes of different nature characterize it. The first process is caused by the diffusion-dissolution of a gas in entrapped penetrant. The second process was recently established in our experiments. The physical mechanism, underlying this development process, is based on a liquid film flow.

For dry developer the process of penetrant's drawing out from defects is similar to the considered above except for the first stage. In this case the development process starts from the capillary penetration of a penetrant into a developer layer.

Introduction: Hydrodynamic model of penetrant's drawing from a defect for the case when dry developer is used has been proposed for the first time in [1]. Later it was elaborated taking into account diffusion-dissolution processes of a gas entrapped in defects hollow [2,3]. At the same time, ensuring acceptable correlation between experimental and calculated date for initial development stage, this model doesn't explain a long-term duration of defects' indication increase, which takes place in many practical cases.

Brief analysis of all basic hydrodynamic and physical-chemical processes development stages, which explains these cases, is presented below. Full theoretical description of the development process depends on geometrical shape of defect's channel and is rather complicated for general case. Therefore let us consider just its basic regulations.

Results and discussion: The process of penetrant drawing from defect's cavity is characterized, as a rule, by three basic stages for wet developer and by two stages – for dry (powder) one. First let us consider the development process in case of wet developer application.

During its initial stage developer layer is still wet, and two various liquids (the penetrant and liquid phase of the developer) are interacting it defect's hollow. This process is described in details in [2,3] and its main rule is following. If the coefficients of surface tension of developer liquid phase (σ_d) and penetrant (σ_p) as well as the angles for wetting of defects wall by the penetrant (θ_p) and by developer liquid phase (θ_d) fulfil the condition $\sigma_d cos\theta_d > \sigma_p cos\theta_p$, then developer liquid phase close the penetrant in a crack and doesn't permit penetrant drawing from defect's cavity till developer layer drying. Thus this inequality corresponds to the disadvantageous case of penetrant inspection.

Nevertheless, as far as developer layer is drying (the considered stage is going to the end), the capillary pressure in the developer $p^c_{dev} = 2\sigma_d(cos\theta_{dev})/R_{av}$ (θ_{dev} – contact angle for wetting of developer particles by the penetrant, R_{av} –average radius of developer's pores [2]) results to penetrant's imbibition into developer layer. At that the smaller average radius of dried developer, the wider is defect's indication.

In the case $\sigma_d \cos\theta_d < \sigma_p \cos\theta_p$, which is preferable for the inspection, even during the first stage (two liquids interaction) when developer layer isn't dry yet, considerable displacement of the penetrant by developer liquid phase is possible that increases both sensitivity and productivity of the inspection.

The second development stage is the capillary penetration of the penetrant from defect's channel into the developer layer. Duration of this stage is in the most cases very short. Capillary pressure in the developer p^c_{dev} represents the main moving force of the process. Both capillary pressure in defect's cavity p^c_d and atmospheric pressure p_a are opposing to this moving force. At the same time the pressure p^{com} of compressed air within the cavity of the crack promotes the process of penetrant's drawing. Our model, which has been proposed and presented in [1], describes just the whole process when dry developer is applied or the second stage of development process when wet developer is used.

This model is based on the formulation of three classical equations and it enables to obtain quantitative characteristics of the kinetics of indication's formation for two considered cases. These equations describe the process of penetrant's drawing out by dry developer. In the case of blind capillary channel with flat parallel walls, considered as a model of defect, these equations can be formulated as follows.

a) Equation for penetrant flow inside defect's channel:

$$-\frac{dl}{dt} = \frac{H^2}{12\mu l}\left[\frac{p_a l_0}{l_0 - l} - \frac{2\sigma_p \cos\theta_p}{H} - p_1(t)\right].$$

(1)

Here l - time-dependent depth of defect's filling with a penetrant; $p_1(t)$ - time-dependent pressure at the defect opening; μ - penetrant viscosity coefficient.

b) Equation for the flow of a penetrant in porous developer layer along the tested surface:

$$\frac{dy}{dt} = \frac{K}{\mu\varepsilon y}\left[p_1(t) + p^c{}_{dev} - p^a\right],$$

(2)

where K -permeability of porous layer, ε - viscosity parameter depending on microstructural characteristics of a penetrant; $y = y\ (t)$ - coordinate of spreading front.

c) Mass conservation condition:

$$n l_0 \psi H = (H + 2y + h)h\Pi + Hl,$$

(3)

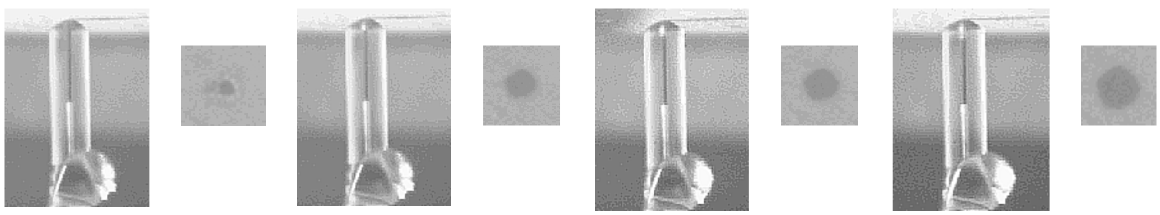
where Π - porosity of the developer; h – developer layer thickness; $\psi = p^c/(p^a + p^c)$; n - factor, which characterises the remaining depth of the defect filling l with the penetrant after excess penetrant removing from the surface directly but before the application of the developer.

The viscosity of polar liquids flowing in porous media can be considerably higher than corresponding reference data, if the average pores radius is smaller than $5*10^{-7}$ m. In this case $\mu = \mu(R_{av}, \varepsilon)$ [4]. In our books [2,3] the analytical expressions for this dependence and the methods to determine the value ε were presented as well. Besides the case of plane-parallel walls crack, similar equations describing penetrant's drawing out from other kinds of defects (cylindrical pores, cracks with plane non-parallel walls) were derived, analysed and described in [3].

As it follows from the equations (1)–(3), to describe quantitatively the development process one needs the values of structural developer's characteristics K, Π, h and $R_{eff}=R_{av}/\cos\theta_{dev}$ as well as n and penetrant's properties μ and σ. The methods of experimental determination of these characteristics have been developed in [2,4].

Obviously the greater the capillary pressure in the developer $p^c{}_{dev}$ as compared with the capillary pressure in defect's hollow $p^c{}_d$, the faster is development process and the greater is the volume of penetrant extracted from defect. At the same time it is appropriate mention here that even at $p^c{}_{dev} < p^c{}_d$ the penetrant drawing out from defect into developer layer takes place. It follows from the fact that before the developer application the penetrant inside the defect was in the equilibrium of surface forces and an appearance of additional (even smaller than $p^c{}_d$) pressure initiates liquid's migration into porous layer.
The most long-term stage of development process is the last - the third one. It is characterized by two basic processes, which are of different physical nature. The first is determined by diffusive penetration processes described in [3]. If diffusive penetration took considerable place during the process of defect's filling with a penetrant, then at subsequent drawing of the penetrant out from the defect the meniscus reaches such a position where the entrapped gas pressure can be lower than p^a. As a result, the depression opposing penetrant's extraction arises. Thus by analogy with diffusive penetration we get an opposite process - so called diffusive extraction of a penetrant from defect's channel. At this process, unlike diffusive penetration, atmospheric air, but not entrapped gas, is dissolving in a liquid. Moreover, it is diffusing inward but not outward like in the case of diffusive penetration. That is the first main reason determinant an increase of development stage duration for revealing smaller defects. The processes of air' dissolution and diffusion during development stage run with a rate several orders lower than the rate of capillary imbibition of the penetrant into developer's layer.
Even more important role in physical processes governing development stage of penetrant inspection plays another physical mechanism of defect's development, which was revealed recently [5]. It is well-known fact that to draw out maximum penetrant entrapment from a defect, the presence of direct contact between a penetrant in defect's mouth and a developer is required. According to EN 571-1 [6] the removal of excess penetrant and following application of developer have to be accomplished in such a way when penetrant should not be wiped out or evaporated. The evaporation of penetrant results in the displacement of meniscus position into defect's channel. An air gap between a penetrant and a developer, subsequently applied to tested surface, arises and hinders their direct contact. Consequently, the drawing of a penetrant from defect's cavity due to capillary penetration should not take place.
Thus direct contact between a penetrant in defect's outlet and a developer may be considered as the most important condition to realize an effective process of penetrant drawing from a cavity of defect. However because of penetrant's evaporation its meniscus may come off defect's outlet. This disturbs development process. Nevertheless, carrying out some special experiments we established that even in the absence of direct penetrant-developer contact the liquid's drawing out from a defect and subsequent formation of an indication take place [5].
Glass cylindrical one-side-closed capillaries of length $l = 3…6$ mm and radius $R = 100…240$ μm were used as model defects. Various kinds of dry and wet developers were used. In the case of dry powder such a developer applied on a glass plate was pressed with a given effort by other glass plate. Wet developers were put also on a glass plate with subsequent drying. As a result of drying process the wet developer forms a uniform, dry, porous structure with good adhesion to a glass plate, which allows conducting researches at different positions of a model defect and developer layer.
The porous layer being in a contact with an outlet of the capillary filled with a penetrant begins to absorb a penetrant. The transparency of a glass allowed observing the processes of forming and growth of an indication. The observations of mass transfer processes were conducted in two directions: from above, with the purpose of visualization the indication, and from sideways for visualization the process of meniscus movement. The capillary was immersed into the penetrant to be filled and thereafter it was wiped with a napkin for removal penetrant excess on the end area. Different contact conditions between a capillary and developer layer were realized as follows. In one case the capillary was wiped dry on a lateral and end area, in the other case the

small drop of a liquid was left on its end. An indication growth was observed using a microscope. Meniscus movement in model defects was observed with a help of video camera.
During our experiments on development process it was established that depending on contact conditions between a liquid in a capillary and developer layer, the liquid drawing from a capillary is explained by one of two different physical mechanisms. When direct contact of a liquid with a porous layer exists and there is no an air gap between a liquid column and powder's particles at the contact moment, then liquid's extraction from a capillary into the developer layer is characterized by classical capillary penetration process. The moving force of imbibition process is here the capillary pressure in porous layer. Development process is comparatively fast and takes place a few seconds. Experimental results and theoretical estimations of kinetic characteristics of the process are in satisfactory agreement.



t = 3 s t = 1 min t = 3 min t = 6 min

Figure. Penetrant's extraction by developer layer in the case of air gap between liquid and developer.

Another case corresponds to the presence of an air gap between a meniscus and porous layer. Video-images of liquid's extraction from the capillary demonstrate rather surprising in terms of traditional penetrant testing ideas. In certain cases an air bubble appears in the region of capillary outlet and cuts off a direct connection between penetrant column and a developer. In spite of this fact the liquid is extracting from a capillary (preliminary filled with a penetrant) into porous layer. One can see from the *Figure* that even in the case of the absence of direct contact between the liquid in defect's channel and developer layer, the formation of defect's indication takes place as well. To the point to note, that the lower meniscus is motionless, and duration of extraction process is large enough (more than 5 min). Therefore the described new development mechanism represents the second reason determinant an increase of development stage duration for revealing smaller defects.
The physical mechanism, underlying this development process, cannot be explained by classical capillary penetration of a liquid into the developer. It follows from our results that new mechanism of penetrant drawing from defect's channel is based on liquid film flow. Thin liquid film flows due to the action of so called disjoining pressure, which is defined as the difference between the normal component of the pressure in a film p_n and the pressure p_0 in a bulk phase of the liquid [7]. Just this mechanism represents one of the main reasons, which cause considerably (2-3 orders) slower running of development stage comparing with two former stages. Accordingly this mechanism explains comparatively long-term development's duration. Besides, the described new development mechanism represents the second reason determinant an increase of development stage duration for revealing smaller defects. Thin liquid film flow is the only mechanism governing the development process in all that cases when "continuity condition" for developer layer structure is disturbed.
So we have considered all three basic stages of development process for the case when wet developer is applied. Their comparative influence upon the indications' size depends on several factors such as volatility of wet developer, physical-chemical penetrant' properties, structural developer' properties, ambient temperature and others.

In the case when dry developer is applied, similar general schema of development stages takes place excluding, obviously, the first stage described above for wet developer. Here the development starts with capillary penetration process of a liquid from defect's hollow into porous developer layer at the moment of their direct contact. This stage is very short-term and runs maximum some seconds. However it doesn't mean that penetrant's volume, extracted by developer layer from defect, is small: in some practical cases after some seconds sharply visible indications can be formed.

The second development stage in this considered case, equivalent to the third stage when wet developer is applied, might run several minutes or even dozens of minutes. It is characterized, as we mentioned above, by the long-term process of diffusion-dissolution of a gas in entrapped penetrant and by penetrant's liquid film flow along both defect' wall and developer' particles surfaces. Exactly due to the processes of this stage one succeed to reveal substantially smaller defects.

Conclusions: Development process can be usually classified in three basic stages for wet developer and in two ones for dry developer.

When wet developer is applied, first takes place inter-replacement of penetrant and liquid phase of the developer. Then during capillary penetration stage the fast extraction of the penetrant from defect's channel into developer porous layer occurs. Finally, slow process of indication increase due to liquid film flow along defect' wall and developer' particles surfaces takes place.

In the case when dry developer is applied, the formation of defect's indication is defined by only two stages described by capillary penetration and by liquid film flow mechanism. At that the duration of the first stage may be considerably (in some cases 2-3 orders) smaller comparing with the second one.

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