

## ВИМІРЮВАННЯ ФІЗИКО-МЕХАНІЧНИХ ПАРАМЕТРІВ РЕЧОВИНИ

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### IMPROVING THE CAPILLARY METHOD OF NON-DESTRUCTIVE TESTING

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Історія капілярного контролю почалася в 40-х роках минулого століття для потреб аерокосмічної промисловості. В даний час вартість контролю якості в аерокосмічній промисловості становить до 12 - 18% від вартості продукції. Подібні обсяги витрат у ядерній та оборонній промисловості не відстають від інших галузей. Наприклад, для контролю зварних з'єднань нафто- і газопроводів великого діаметру і великої довжини витрати праці на інспекцію досягають 10% від загальної вартості робочої сили. Метод капілярного контролю якості заснований на здатності індикаторних рідин проникати в порожнини поверхневих дефектів (розривів). За 70 років свого існування капілярний метод контролю не зазнав кардинальних змін, і його принципи залишилися незмінними. У міжнародній практиці прийнято скорочене позначення типів неруйнівного контролю (АРМ), а контроль з використанням проникаючої рідини позначається РТ. Цей метод застосовується для виявлення всіх типів поверхневих глухих і дефектів, таких як тріщини, розшарування, витоки, в виробках, виготовлених з будь-яких непористих матеріалів, включаючи скло, кераміку, пластмаси та інші неметалеві матеріали. Здійснено аналіз капілярного методу неруйнівного контролю поверхні твердого тіла, показані можливості та шляхи його поліпшення. Детально розглянуто метод капілярного методу неруйнівного контролю твердої поверхні, фізики способу та його реалізації. Показано, що змочувальна здатність і розтікання є важливими характеристиками капілярних контрольних рідин; отже, вони повинні бути оцінені та проаналізовані при розробці нових, виборі або порівнянні відомих матеріалів капілярної дефектоскопії. Доведено можливість використання ефекту Ребіндера для вдосконалення капілярного методу неруйнівного контролю твердої поверхні. Запропоновано уточнений метод капілярної дефектоскопії з урахуванням змочувальної здатності, щільності, в'язкості та випаровування рідини, що дозволяє зробити оптимальний вибір рідини для забезпечення високої ефективності поверхневого (капілярного) контролю. Запропоновано вдосконалений метод оцінки змочувальної здатності рідин, що дозволяє оцінити змочуваність рідин за розміром місця розтікання їх крапель, враховуючи вплив щільності, в'язкості та випаровування рідин, призначених для капілярної дефектоскопії.

**Ключові слова:** неруйнівний контроль, капілярний метод, проникність, дефектоскопія.

История капиллярного контроля началась в 40-х годах прошлого века для нужд аэрокосмической промышленности. В настоящее время стоимость контроля качества в аэрокосмической промышленности составляет до 12 - 18% от стоимости продукции. Подобные объемы расходов в ядерной и оборонной промышленности не отстают от других отраслей. Например, для контроля сварных соединений нефте- и газопроводов большого диаметра и большой длины затраты труда на инспекцию достигают 10% от общей стоимости рабочей силы. Метод капиллярного контроля качества основан на способности индикаторных жидкостей проникать в полости поверхностных дефектов (разрывов). За 70 лет своего существования капиллярный метод контроля не претерпел кардинальных изменений, и его принципы остались неизменными. В международной практике принято сокращенное обозначение типов неразрушающего контроля (АРМ), а контроль с использованием проникающей жидкости называется РТ. Этот метод применяется для выявления всех типов поверхностных глухих и дефектов, таких как трещины, расслоения, истоки, в изделиях, изготовленных из любых непористых материалов, включая стекло, керамику, пластмассы и другие неметаллические материалы. Осуществлен анализ капиллярного метода неразрушающего контроля поверхности твердого тела, показаны возможности и пути его улучшения. Подробно рассмотрен метод

капиллярного метода неразрушающего контроля твердой поверхности, физики способа и его реализации. Показано, что смачивающая способность и растекания являются важными характеристиками капиллярных контрольных жидкостей; следовательно, они должны быть оценены и проанализированы при разработке новых, выборе или сравнении известных материалов капиллярной дефектоскопии. Доказана возможность использования эффекта Ребиндера для совершенствования капиллярного метода неразрушающего контроля твердой поверхности. Предложено уточненный метод капиллярной дефектоскопии с учетом смачивающей способности, плотности, вязкости и испарения жидкости, что позволяет сделать оптимальный выбор жидкости для обеспечения высокой эффективности поверхностного (капиллярного) контроля. Предложено усовершенствованный метод оценки смачивающей способности жидкостей, позволяет оценить смачиваемость жидкостей по размеру места растекания их капель, учитывая влияние плотности, вязкости и испарения жидкостей, предназначенных для капиллярной дефектоскопии.

**Ключевые слова:** неразрушающий контроль, капиллярный метод, проникаемость, дефектоскопия.

The history of capillary control began in the 40s of the last century for the needs of the aerospace industry. Currently, the cost of quality control in the aerospace industry is up to 12 - 18% of the cost of products. Similar amounts of expenses in the nuclear and defense industries are not lagging behind other industries. For example, for the control of welded joints of oil and gas pipelines of large diameter and considerable length, the labor costs for inspection reach 10% of the total labor costs. Capillary quality control method is based on the ability of indicator liquids (penetrants) to penetrate into the cavities of surface defects (discontinuities). Over the 70 years of its existence, the capillary method of control has not undergone fundamental changes, and its principles have remained unchanged. In international practice, the abbreviated designation of types of non-destructive testing (AWS) is adopted, and the control with the use of penetrating liquid denoted RT. This method is applicable to the detection of all types of surface dead-end and through defects, such as cracks, delamination, leaks, in products made from any non-porous materials, including glass, ceramics, plastics and other non-metallic materials. The analysis of the capillary method of non-destructive testing of the surface of a solid body is carried out, the possibilities and ways of its improvement are indicated. The method of the capillary method of non-destructive testing of a solid surface, the physics of the method and its implementation are considered in detail. It is shown that the wetting ability and spreading are important characteristics of capillary control fluids; therefore, they must be evaluated and analyzed when developing new ones, choosing or comparing known capillary flaw detection materials. The possibility of using the Rebinder effect to improve the capillary method of non-destructive testing of a solid surface has been proved. A refined method of capillary defectoscopy is proposed by taking into account the wetting ability, density, viscosity and evaporation of a liquid, which makes it possible to make an optimal choice of liquid to ensure high efficiency of surface (capillary) control. An improved method for assessing the wetting ability of liquids is proposed, which makes it possible to evaluate the wetting ability of liquids by the size of the spreading spot of their droplets, taking into account the influence of density, viscosity and evaporation of liquids intended for capillary flaw detection (penetrants).

**Keywords:** non-destructive control, capillary method, penetrations, flaw detection

## Introduction

The history of capillary control began in the 40s of the last century for the needs of the aerospace industry. Currently, the cost of quality control in the aerospace industry is up to 12 - 18% of the cost of products. Similar amounts of expenses in the nuclear and defense industries are not lagging behind other industries. For example, for the control of welded joints of oil and gas pipelines of large diameter and considerable length, the labor costs for inspection reach 10% of the total labor costs.

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practice, the abbreviated designation of types of non-destructive testing (AWS) is adopted, and the control with the use of penetrating liquid denoted RT. This method is applicable to the detection of all types of surface dead-end and through defects, such as cracks, delamination, leaks, in products made from any non-porous materials, including glass, ceramics, plastics and other non-metallic materials. The capillary control method is allowed at ambient temperatures from  $-40^{\circ}\text{C}$  to  $+40^{\circ}\text{C}$  and relative humidity not exceeding 90%. The most effective capillary method for non-destructive testing of large areas (especially with complex geometry). For example, equipment for oil and gas pipelines, chemical and oil refining industries, pressure vessels, etc., taking into account that many of them have already exhausted their resources.

## Methods

According to the current GOST 18442-80 [1], capillary non-destructive testing methods are classified as:

- Brightness (achromatic).
- Color (chromatic).
- Luminescent.
- Luminescent and color.

Depending on the method of identifying the indicator pattern, capillary control methods are divided into

- Luminescent method (for especially important assemblies and parts), based on registration of the contrast, luminescent in the long-wave ultraviolet radiation of the visible indicator pattern, against the background of the surface of the test object;

- Color method, based on the registration of the contrast of the color in the visible radiation of the indicator pattern on the background of the surface of the test object.

With a sufficient degree of accuracy, the hydrodynamics of the flow of indicator liquids in capillaries obeys the equations derived for Newtonian fluid. Newtonian fluid obeys in its flow the Newton's viscous friction law, that is, the shear stress and velocity gradient in such a fluid are linearly dependent. The proportionality coefficient between shear stress and velocity gradient is the viscosity of the indicator liquid. Penetrants (indicator liquids) are made, as a rule, on the basis of kerosene and alcohol [2-4].

Penetrants fill the end-to-end and dead-end capillary in various ways. In a dead-end capillary, the vapor-air mixture, locked in the depth of the capillary, limits the depth of penetration, and the filling proceeds in two stages. At the first stage (capillary stage), the indicator liquid under the action of capillary forces begins to quickly penetrate into the depth of the defect and ends when the capillary pressure of the liquid approaches the pressure of the vapor-gas mixture in the dead end capillary. The second stage is the diffusion stage, when the gas compressed in the cavity of the defect gradually dissolves in the indicator liquid and diffuses to the mouth of the defect [5, 6]. Therefore, it is of practical interest to identify patterns of filling with various liquids [7-11] and a comprehensive assessment of the wetting process of solid surfaces with a liquid [12].

## Results and discussion

The main feature of the capillary control method is the absence of significant and non-essential operations. Each operation does not allow negligence, any missteps, deviations from the technology; any of these errors negates all previous efforts, because it is almost impossible to correct the mistakes. To detect dangerous defects, it is necessary to reproduce the capillary control from the very initial operation.

In capillary inspection operations, the surface of the defect comes into contact with various flaw detection materials. As it is known, the necessary conditions for the detection of defects by the methods of penetrating liquids are the absence of pollution and other foreign substances both in the discontinuity itself and in its mouth to penetrate the penetrant into it, as well as good wettability by the penetrant of the material of the test object. At the same time, the depth of defects should significantly exceed the width of the penetrant opening.

**Table 1.** Comparison of non-destructive testing methods by defect size and sensitivity according to AMS-2644 standard.

| Method       | Crack opening, micron | Sensitivity level |
|--------------|-----------------------|-------------------|
| Capillary    | 0,2                   | IV                |
| Ultrasonic   | 5                     | III               |
| Eddy current | 10                    | III               |
| Visual       | 50                    | II                |

It should be noted that the sensitivity levels according to AMS-2644 are directly opposite to GOST 18442-80.

As is known, for the capillary control, various physical and functional-technological properties of indicator liquids (penetrants) are important. During the development and selection of indicator liquids (penetrants) for use in capillary control, their various physical and functional-technological properties are examined: surface tension, viscosity, dissolving ability, diffuse and color characteristics, corrosivity, etc.

A longer penetration time (longer discontinuity) holds a greater amount (volume) of tracer fluid in the damage (crack). Drying of the penetrant on the test surface is also not allowed; therefore, the test surface must be wetted by the penetrant during the entire time of capillary control. The resulting pattern is a "trace of a defect" and is subject to processing for visual inspection.

In capillary control, the length of damage (cracks) is usually the main parameter of the size of the indicator pattern, which ensures its visual detection. In capillary control, the shape of the wake and its geometrical characteristics (area, length and width), as well as energy characteristics — the contrast of the indicator pattern and its brightness are decisive factors. The sensitivity of capillary control methods is determined by the ability of a set of flaw detection materials (penetrants) to detect discontinuities of a given minimum width of disclosure at a certain depth, and actually reaches 0.2-0.5  $\mu\text{m}$ . Moreover, the more the defect is filled with penetrant, the greater the likelihood of its detection. Detection of defects having a disclosure width of more than 0.5 mm is not guaranteed by capillary methods. The author was faced with the real problem of determining a defect when the ratio of the depth of the defect to its width is less than 9.

Very thin cracks and damage create a drawing that is too narrow for visual inspection. For example, the author's studies showed that surface pattern of 1.32 mm length in 94% of cases can be detected and surface pattern of 0.23 mm in length - only in less than 33% of cases (studies were conducted with a confidence of 0.95). Similar and comparable data were also obtained by colleagues in [13].

Flaw detection materials are selected depending on specific requirements. From the point of view of the

author, for the field conditions the most versatile and optimal is the MAGNAFLUX SK3-S Kit (United Kingdom) (Fig. 1). Defects are detected as bright, clear red lines on a white background. This kit conducts surface inspection of any non-porous surfaces at temperatures from 0 ° to 65 ° C for surface defects ranging in size from 1 micron. Nevertheless, the author received satisfactory results for the control of surface defects at - 3 ° C. Which is much better than the popular set of Sherwin (USA).



**Fig. 1. Flaw detector kit MAGNAFLUX SK3-S Kit (UK).**

Known methods for assessing the wetting ability of liquids intended for capillary flaw detection are imperfect. In liquids intended for capillary flaw detection (penetrants), there is no static equilibrium wetting angle. They spread well on the surface of a solid and form a variable (dynamic) wetting angle, the value of which is close to zero. Therefore, to assess the wetting ability it is necessary to use metal capillaries. It is very difficult to determine the height of raising liquids in a metal capillary with the required accuracy. Therefore, the author has developed an improved method for comprehensive assessment of the process of wetting with liquids and spreading over the surface of solids.

The most common in capillary flaw detection method is a comparative assessment of the wetting ability of

liquids by measuring the radius or diameter of a spot formed by a drop of the normalized volume of the test liquid that spreads on a horizontal solid surface at a given temperature over a set time, or determining the change in the diameter of this spot with time (spreading rate). It is believed that the greater the radius (diameter or area) of the spreading spots, ceteris paribus, the better the wetting ability of the liquid. However, in this way, it is not wetting ability that is evaluated as the degree of interaction between a solid and a liquid and their ability to form a stable liquid-solid surface, and spreading. Nevertheless, wetting and spreading are two different, albeit related physico-chemical phenomena, which correspond to two different parameters of the quality of liquids.

As shown in [12], the wetting ability is a function of surface tension (specific free surface energy) and does not depend on viscosity, density, and other fluid parameters (it can depend only on temperature). Since the wetting ability and spreading are important characteristics of capillary control fluids, they must be evaluated and analyzed when developing new ones, choosing or comparing known capillary flaw detection materials. Therefore, the author conducted research on changes in the radius (diameter or area) of the spreading spot depending on these parameters in the hydrodynamic viscous mode. During the experiment, the spreading time ranged from tens of seconds to several minutes. An empirical relationship was obtained, which allows the wetting ability of liquids to be estimated from the size of the spreading spot of their droplets, taking into account the effect of density, viscosity and evaporation of the liquid. The author has developed a method for integrated assessment of the spreading of liquids intended for capillary flaw detection [12]. According to the proposed method, the wetting and spreading of liquids intended for capillary flaw detection can be assessed in one experiment.

The results of a comparative evaluation of the wetting ability of liquids by known and proposed methods are given in [12]. From the conducted studies of the author, it was revealed that the results of the evaluation of the wetting ability of some liquids (3, 4, 7, 8) by the known and proposed methods are the same. For example, liquid 1, which, as was considered on the basis of evaluations in a known manner, has a low wetting ability (fifth place in this parameter among the liquids studied), actually has a high capacity (second place in the assessment by the proposed method), and the relatively small diameter of the liquid spreading spot due to its high evaporation due to the presence of gasoline in its composition (specific evaporation of this liquid is equal to  $6.605 \cdot 10^{-4} \text{ g / cm}^2 \cdot \text{min.}$ , whereas for other liquids, which took on wetting the first four places, it does not exceed  $1.36 \cdot 10^{-4} \text{ g / cm}^2 \cdot \text{min.}$ ). On the contrary, liquid 2 has a slightly reduced wetting ability (3rd place in the assessment by the method proposed by the author), and the large diameter of its spreading spot (and, consequently, a high estimate of wetting ability in a known manner) is due to reduced evaporation ( $1.085 \cdot 10^{-4} \text{ g / cm}^2 \cdot \text{min.}$ ) [12].

In the work [12], the author proposed a refined method of capillary flaw detection by taking into account the wetting ability, density, viscosity and evaporation of a liquid, which makes it possible to make an optimal choice of liquid to ensure high efficiency of surface (capillary) control, as well as a refined method for assessing the wetting ability liquids, which allows to evaluate the wetting ability of liquids by the size of the spot spreading their droplets, taking into account the influence of density, viscosity and evaporation of liquids.

The effects of ultrasound on liquids and various effects were studied by various researchers: acoustic cavitation, vortex effects, ultrasonic capillary effect, acceleration of diffusion processes, electrokinetic phenomena, etc. [14-17]. To improve the penetrant filling, the author attempted to use the Rebinder effect. The effect of Rebinder makes it easier to disperse under the influence of adsorption - the process at the interface of two phases due to the uncompensated intermolecular interaction forces in their section.

The advantage of the Rebinder effect over other physical phenomena is:

- With an accompanying mechanical effect on a solid body, an insignificant volume of the substance is sufficient;
- Immediate manifestation after contact of the body with the environment.
- After removal of the medium, the body returns to its original characteristics.

To manifest the Rebinder effect, it is necessary to have tensile stresses and contact of a solid with a liquid.

To this end, the author conducted a series of studies on the effect of ultrasonic waves on the penetration of substances in the discontinuity of the material of the structures. From publications it is known that similar work was carried out by other researchers. For example, in the Ivano-Frankivsk University of oil and gas. However, it was not possible to find the confirmed results and the research report.

Studies have shown a significant increase in kinetic energy, which is partially transformed into a power pulse and into thermal energy of collapsing bubbles in the capillary when the ultrasound intensity is more than  $105 \text{ W/m}^2$ . This is caused by two types of ultrasonic cavitation. Inertial cavitation associated with the formation of vapor-gas cavities in a liquid due to the stretching of the liquid during the negative half-period of oscillations in the acoustic wave and abrupt collapse of these cavities in the half-period of compression. Non-inertial cavitation, characterized by oscillations of long-existing, stable gas bubbles. The slamming bubbles in the capillary create shock waves, the pressure of which reaches  $10^8 \text{ Pa}$ . That is, in the capillary, under the influence of ultrasound, electrokinetic phenomena arise due to the directed movement of charged particles, which influence the diffusion processes.

Similar results were obtained by the Belarusian colleagues [18].

In the course of the experiment, it was found that as a result of the ultrasonic effect on wetting (the Rebinder effect) there was a significant increase in the penetrant penetration into the cavity of the defect. Thus, it is determined that the penetration of the penetrant into the defect can be significantly improved if the process is carried out in an ultrasonic field based on the Rebinder effect.

## Conclusions

The capabilities of the capillary control method can be significantly improved with the help of a complex of modern physicochemical approaches using physical and chemical effects due to the intensity of the interaction of penetrating substances - penetrants with the surface of a controlled defect.

An improved method for assessing the wetting ability of liquids is proposed, which makes it possible to evaluate the wetting ability of liquids by the size of the spreading spot of their droplets, taking into account the influence of density, viscosity and evaporation of liquids intended for capillary flaw detection (penetrants). The method is necessary in the design and selection of penetrants.

A refined method of capillary defectoscopy is proposed by taking into account the wetting ability, density, viscosity and evaporation of a liquid, which makes it possible to make an optimal choice of liquid to ensure high efficiency of surface (capillary) control.

Penetration of the penetrant into the defect can be significantly improved if the process is carried out in an ultrasonic field based on the Rebinder effect.

It is shown that the wetting ability and spreading are important characteristics of capillary control fluids; therefore, they must be evaluated and analyzed when developing new ones, choosing or comparing known capillary flaw detection materials.

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