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IMPROVEMENT OF PENETRANT-TESTING METHODS

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A study has been made of the influence of different factors (characteristics of technological stages of testing, roughness of the tested surface, and thermal effects) on the sensitivity and efficiency of nondestructive-penetrant-testing methods. Facilities for quantitative evaluation of the sensitivity of sets of flaw-detector materials and indicator liquids and the technological regime of testing with blowing of the tested surface with warm air, in which the sensitivity and efficiency of flaw detection of penetrant-testing methods increase significantly, have been developed.

Keywords: *liquid-penetrant testing, thermal effect, roughness, electrochemical treatment.*

Introduction. Methods and facilities for nondestructive testing and technical diagnostics are of primary importance when the problems of upgrading commercial products and ensuring safe operation of industrial objects are solved. The range of application of liquid-penetrant testing methods is being extended every year due to a number of reasons. This is primarily due to the highest sensitivity of these methods (today's flaw-detector materials make it possible to safely detect cracks with an opening width of to 0.5 μm). Another important reason is the steadily growing use of heatproof steels, aluminum, titanium, and other nonmagnetic alloys, and ceramic, composite, and polymer materials as structural materials. In many cases the only possible method of detecting surface cracks with an opening width of less than 1 μm is liquid-penetrant testing. Furthermore, an important advantage of the methods of liquid-penetrant testing compared to other forms of nondestructive testing is their applicability to testing surfaces with an intricate geometric profile and the low cost of testing devices.

At the same time, the applicability of these methods is limited, first, by the requirements on surface roughness (it may not be high), and, second, by the possibility of detecting only exposed discontinuities with them. Also, a substantial drawback of liquid-penetrant testing methods, which are multioperational, is their labor intensity. Therefore, the issue of development of both means of applying liquid-penetrant-testing methods to rough surfaces and the optimum technological regimes of all stages of testing used to detect surface defect, is of special importance.

At the Institute of Applied Physics of the National Academy of Sciences of Belarus, the lines of investigation of different means of increasing the efficiency of liquid-penetrant testing are as follows: development of new devices for determination of the sensitivity of flaw-detector materials, optimization of the parameters of basic technological stages of liquid-penetrant testing, use of thermal effects for increasing the efficiency of the process of testing, and development of methods and devices for liquid-penetrant testing of objects with a high surface roughness. Below, we briefly consider investigation results obtained within the framework of these lines.

New Devices for Determination of the Sensitivity of Flaw-Detector Materials. As is well known, the most important elements of determination of the sensitivity of flaw-detector materials are specified check samples satisfying the conditions of detectability of defects in them in accordance with the procedure of the new standard ISO 3452-2:2006(E) and means of quantitative evaluation of the indicator traces of these defects, which appear when the tested set is used.

Check samples for determination of the sensitivity of sets of flaw-detector materials, which are recommended by the EN ISO 3452-3 standard, represent a set of four brass plates of a rectangular shape. It is precisely these check samples that are used rather widely in the countries of Western Europe (and in Russia, Belarus, and some other CIS countries in recent years). Determination of the sensitivity level of the set of flaw-detector materials with them encounters a substantial drawback: the results turn out to be strongly overstated on frequent occasions. This is due to the Π

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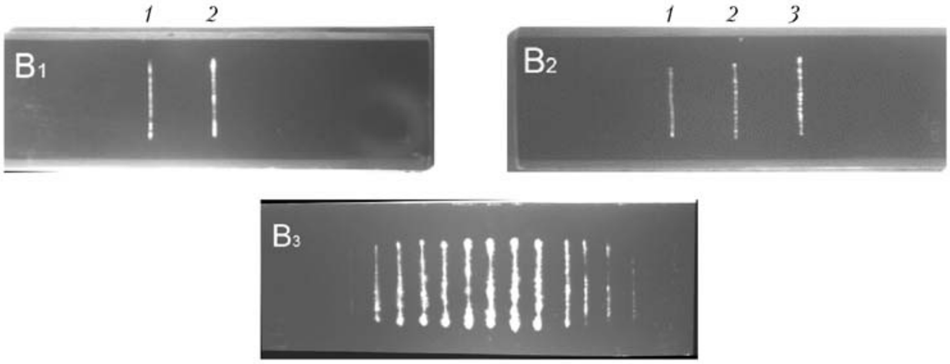

Fig. 1. Samples for liquid-penetrant flaw detection (fluorescent testing): 1–3) defect numbers: B_1 (AISI 430 steel), the depths of all the defects are the same (~400–450 μm); the opening widths are: 1) 1–1.5 μm and 2) 2.5 μm; B_2 (AISI 430 steel), the opening widths at all the defects are the same (~1.5 μm); the depths are: 1) 150 μm, 2) 300 μm, and 3) 450 μm; B_3 (15Kh5M steel), the defect depths are ~400–550 μm, the opening widths are 1–11 μm.

shape of cracks *emerging on the lateral surfaces* in such samples, since they appear on cracking of the surface layer *throughout the plate's width*. As a consequence, when a penetrant is applied to the sample, surface air is easily extracted from the cavity of such a crack almost without keeping the liquid from penetrating into it. As a result, a low-sensitivity penetrant in certain cases can ensure a rather bright high-contrast indicator of traces of cracks that, erroneously correspond to a higher sensitivity level.

The penetration of a penetrant into crack-type defects that are formed in the central region of the surface of the material itself of a plate not having a special surface layer applied to it is different. In this case, first, the air closed in the defect's cavity keeps it from being rapidly and totally filled with penetrant and, second, it is much easier to ensure the identity of the characteristics of such impregnation during some operations. The technology of manufacture of check samples with crack-type defects having a prescribed opening width of tenths of fractions to several micrometers or higher has been developed at the Institute of Applied Physics of the National Academy of Sciences of Belarus. This technology makes it possible to obtain a number of defects on one sample and to prescribe their depth and length in a fairly wide range (Fig. 1). The samples have the shape of rectangular plates with dimensions 100 × 30 × 6 mm. They are manufactured from ferritic stainless magnet steel that possesses a good combination of high corrosion and magnetic properties. This enables us to use such samples for determination of the sensitivity of a magnetic-particle testing method, too. An important advantage of these check samples is their much lower cost than that of the check samples described in EN ISO 3452-3.

Evaluation of the sensitivity of sets of flaw-detector materials is based on measuring the characteristics of indicator patterns. The technique of photographing of the tested surface followed by an analysis of the characteristics of the indicator patterns of defects and of the method based on the use of the distinctive features of the contrast sensitivity of vision in direct observation of an object of investigation are employed as a rule. Evaluation of the characteristics of indicator patterns with these techniques is subjective in character and does not ensure high accuracy, which considerably diminishes, as the geometric shape of the indicator patterns is complicated. Moreover, the results of such evaluation are qualitative in character and are strongly dependent on the physical state and experience of a flaw-detection specialist. Therefore, it is topical to develop the method of evaluation of the quality of sets of flaw-detector materials and to select means and techniques of recording results of liquid-penetrant testing that ensuring objective quantitative results.

A computerized setup for processing and analysis of video images has been developed at the Institute of Applied Physics of the National Academy of Sciences of Belarus in cooperation with associates from the Federal Institute of Materials Research and Testing (Berlin, Germany) for solution of these problems. A TV system making it possible to find and automatically record small-size and low-contrast indicator patterns of defects used in this setup as a device recording test results. The software developed at the Institute makes it possible to rapidly make objective quantitative evaluation of the visibility of indicator patterns on the basis of measurement and analysis of their optical and geometric characteristics.

Optimization of the Parameters of Basic Technological Stages of Liquid-Penetrant Testing. On the basis of the results of the experimental and theoretical investigations of recent years carried out at the Institute of Applied Physics of the National Academy of Sciences of Belarus [1–4], we have developed a number of practical recommendations on selection of the parameters of different technological stages of liquid-penetrant testing with the aim of increasing its sensitivity and efficiency. For example, it has been shown that when the sensitivity of a prescribed set of flaw-detector materials is determined with check samples for durations of the stages of application of the penetrant and the developer of longer than 1 min, further increase in them influences the detectability of defects only slightly. However, for the tested products where the defect depth may exceed 50 μm, increase in the time of impregnation (penetration) of the tested surface by the penetrant and in the time of development of defects to 10 min leads to a substantial growth in their detectability and in the sensitivity of the entire testing.

In our experimental investigations, we have found certain distinctive features of the influence of the procedure of application of a developer to the tested surface [1, 3]. It has been established that in evaluating both the sensitivity of the set of flaw-detector materials and results of practical liquid-penetrant testing, two factors dependent on the character of application of the developer to the tested surface and influencing the shape, width, and brightness of the indicator traces of defects are of importance. These are the thickness of the developer layer and the dynamic effect of the particles of the applied developer (velocity and angle of incidence of the particles on the tested surface).

For each prescribed set of flaw-detector materials, there is an optimum value of the developer-layer thickness. For a small layer thickness where individual particles (or their conglomerates) above the crack mouth are not in contact with the basic penetrated region of the developer, the indications experience discontinuities, which impairs their visibility. On the other hand, excess over the optimum value of the developer-layer thickness leads to the fact that the width of the penetrated region of the exterior surface of the developer layer decreases and flaw detectability is accordingly impaired. The optimum developer-layer thickness is ensured by selection of the corresponding duration of the stage of application of the developer and the distance from the injector to the tested surface. The results of the investigations have shown that, e.g., with a Helling D70 developer, the optimum layer thickness for a portion of length 250 mm is ensured by a uniform spraying of the suspension from the spray for 3 sec at a distance of 300 to 350 mm from the tested surface. We emphasize that instructions for use of developers, which have been prepared by the manufacturers themselves, contain substantially understated recommended distances from the injector to the tested surface in some cases.

In the most widespread technique of application of a suspension developer, i.e., in aerosol spraying, the dynamic effect of the aerosol cloud on the character of formation of indicator traces of defects can manifest itself as the occurrence of a pronounced small-scale sinusoity of the indicator-trace lines when the distance between the injector and the tested surface is small. This leads to smeared indications and as a consequence to their lower contrast against the surrounding background (Fig. 2a). As the distance between the injector and the tested surface increases, the tortuosity of indications disappears (Fig. 2b). We have an analogous effect in the cases where the aerosol jet is directed to the tested surface at an angle significantly different from 90°.

In evaluating the sensitivity of sets of flaw-detector materials and the results of liquid-penetrant testing, the same conditions of application of the developer to the tested surface, which correspond to the optimum layer thickness and the absence of the shift of developer particles in the process of increase in the layer thickness, are required to ensure the repeatability of results.

Also, we have investigated the *relationship between the viscosity and the sensitivity level of indicator liquids.* We determined the viscosities of eight popular penetrants (six fluorescent penetrants (FP_i, $i = 1, ..., $ and 6) and two dye-type penetrants (DP, $i = 1$ and 2)). As is seen from Table 1, the most sensitive penetrants have a higher viscosity; increase in the sensitivity of different indicator liquids corresponds to the growth in their viscosity. Measurements were carried out on an VIR 78 MÉ microelectrorheometer.* The sensitivities correspond to a five-level classification of the new edition of the ISO EN 3452-2 Standard. Thus, the best detectability of surface defects is ensured, as a rule, by penetrants with a higher-than-average viscosity. The use of indicator liquids with a higher-than-average viscosity is par-

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*The authors express their thanks to Candidate of Sciences in Engineering V. A. Mansurov for measuring the penetrant viscosity.

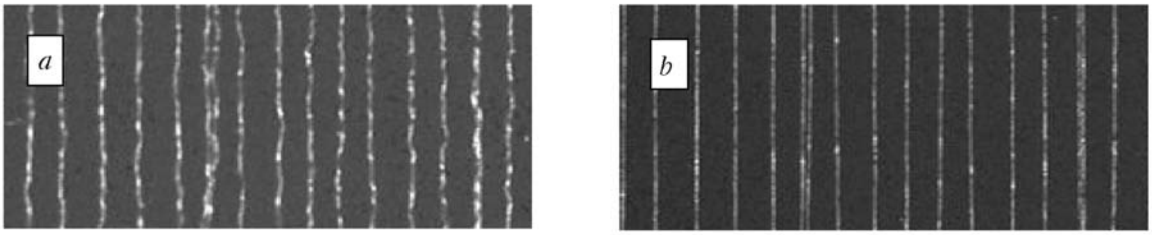

Fig. 2. Indications of cracks of depths 17 μm and opening 0.9 μm under different conditions of application of he developer: the distance form the injector to the tested surface is 30 cm (a) and 90 cm (b).

TABLE 1. Viscosity of Different Penetrants at a Temperature of 18°C

Indices	FP$_1$	FP2	FP3	FP4	FP5	FP6	DP1	DP2
Sensitivity level	0.5	3	2	2	4	0.5	1	0.5
Viscosity, mPa·sec	6.33	14.11	10.7	13.62	56.01	2.17	5.84	3.78

ticularly efficient in testing vertically arranged surfaces of diagnosed objects. In this case we ensure not only a high sensitivity but also a sufficient duration of contact between the liquid and the defect mouth, since a high-viscosity penetrant more slowly flows down the tested surface. We should, however, take into account that an increase in the viscosity of penetrants means smaller amounts of their excess are washed away before the application of the developer.

The results described above and other investigation results have made it possible to develop and use, at a number of enterprises, practical recommendations on optimization of the parameters of technological stages of liquid-penetrant testing with the aim of increasing its sensitivity and reliability. For example, a procedure of liquid-penetrant testing of welds of technological pipelines and welded joints of pump- and compressor-equipment parts, which was developed at the Institute, has been brought into commercial practice at the "Mozyr' Oil Refinery" Public Corporation.

Use of Thermal Effects for Increasing the Efficiency of the Testing. Under winter conditions when the air temperature is negative, the duration of drying of a suspension-developer layer applied to the tested surface is longer than tens of minutes on frequent occasions. This sharply diminishes the efficiency of the process of liquid-penetrant testing, which can be a critical factor when tested volumes are large. Investigations with the aim of increasing the efficiency at low air temperatures were carried out at the Institute of Applied Physics of the National Academy of Sciences of Belarus.

In [2], we have carried out investigations with the aim of establishing the qualitative and quantitative regularities of the influence of the duration of drying of layers of suspension developers of various grades on the flaw detectability. In the experiments, we established a distinct regularity: the smearing of the indicator trace increases with the duration of drying of the developer layer, which accordingly impairs the visibility of the detected defect. For example, the rate of drying of an MR70-developer layer is nearly twice as high as that of a Bycotest D 30-developer layer applied to the same surface portion of a check sample with cracks under identical conditions. From Fig. 3a, it is clear that the MR70 developer gives much higher-contrast indicator traces than the Bycotest D 30-developer (Fig. 3b). In both cases the check samples are treated with the same penetrant under identical conditions.

Here we should also note that there is a number of quick-drying developers that form a porous layer on the surface of the tested object over a period no longer than 3 min at the ambient temperature $T \geq 18^{\circ}$C. Experimental investigation of the kinetics of formation and growth of the indicator traces of defects with such developers shows that within 3 to 5 min after their application to the surface, the trace ceases to grow. An analogous situation is observed for long-drying developers (time of complete drying 5 min or longer) with a small thickness of the applied layer. In this connection, in testing welds and parts, it is recommended that a development time of 5 to 10 min depending on the developer grade be ensured with the complete drying of the layer.

The software developed at the Institute of Applied Physics of the National Academy of Sciences of Belarus using the computerized setup for processing and analysis of video images makes it possible to quantitatively evaluate the optical and geometric characteristics of indicator patterns. We have investigated the *influence of the ambient temperature on the developing properties of developers*. The same fluorescent penetrant Magnaflux ZL-19B was used as

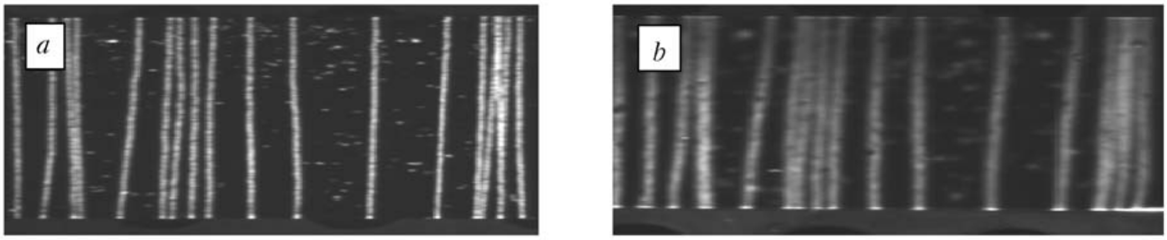

Fig. 3. Indicator pattern in the case of the use of developers with different degrees of volatility of the liquid phase: MR70 (a) and Bycotest D-30 (b).

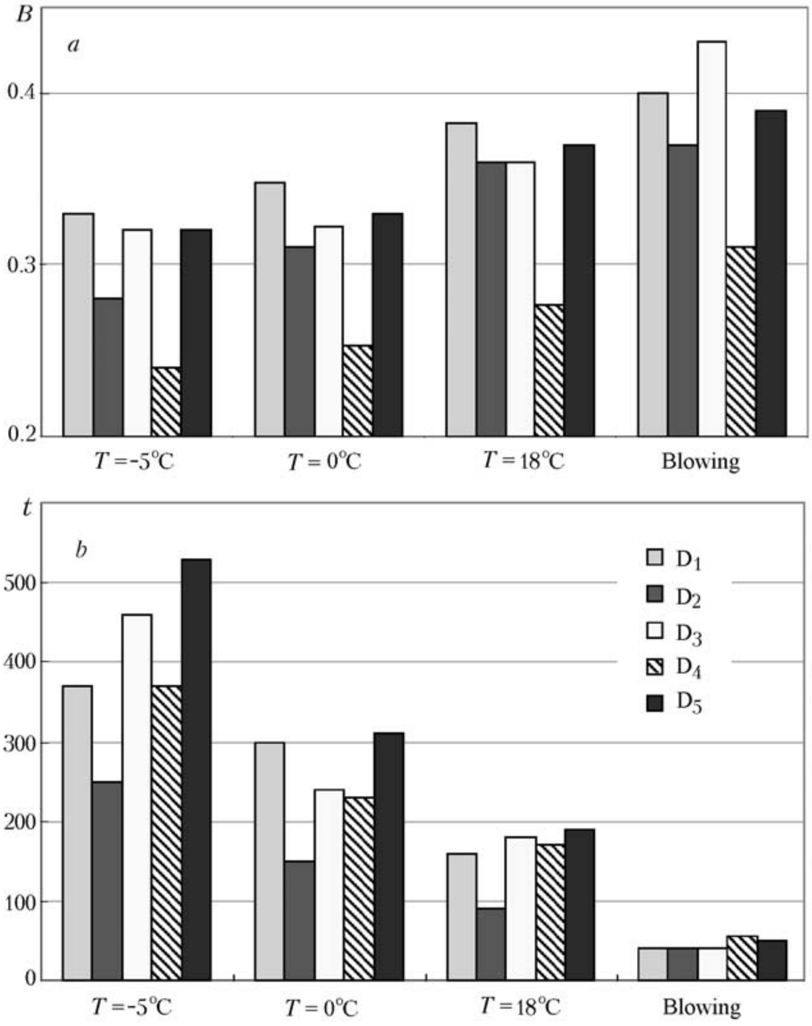

Fig. 4. Values of the average brightness of the trace B (a) and the drying time of the developer layer t (b) for certain grades of suspension developers (D_1–D_5) at different ambient temperatures and with hot-air blowing. B, relative units; t, sec.

the indicator liquid for developers of five different manufacturers (D_1–D_5). The experiments were carried out at the ambient temperature $-12^{o}C < T < 18^{o}C$. Blowing with hot air with a jet temperature of $+40^{o}C$ was used. In this case, e.g., the air temperature at the sample's surface reached $+15^{o}C$ at an ambient temperature of $-10^{o}C$.

As a result of the investigations, it has been established that when a surface microcrack is detected with a prescribed fluorescent set of flaw-detector materials, the contrast and the brightness B of the indicator pattern of the defect substantially decrease with ambient temperature. This corresponds to the results (mentioned above and illustrated by Fig. 3) of investigations of the influence of the duration of drying of layers of suspension developers of various grades on the flaw detectability [2, 4]. Thus, at negative temperatures ($T < 0^oC$), the indications are less bright and more smeared without hot-air blowing.

The obtained results are illustrated by the diagrams in Fig. 4. E.g., at the ambient temperature $T = -5^oC$, the average brightness B of the fluorescent indicator microcrack trace when developer D_3 is used is 0.32 rel. units; in blowing, it is 0.43 rel. units (Fig. 4a). It is significant that the duration of complete drying of the layer of the above developer is 460 sec in the case of testing at a temperature of -5^oC, whereas in warm-air blowing, it diminishes to 40 sec (Fig. 4b). Thus, in addition to the considerable increase in the efficiency of testing, this regime contributes to the larger degree of extraction of the penetrant from the cavities of defects, ensuring increase in the testing sensitivity [5].

As a result of the investigations, we have determined the grades of popular flaw-detector materials on the market of nondestructive-testing facilities, whose use ensures the maximum efficiency and sensitivity of liquid-penetrant testing under winter conditions. Also, we have proposed the technological regime of testing with blowing of the tested surface with warm air, in which not only does the duration of the development stage become an order of magnitude shorter, but much brighter and higher-contrast indicator patterns of the detected defects are ensured as well. The obtained results make it possible to more efficiently solve the problem of increasing the efficiency of liquid-penetrant testing at low air temperatures under winter conditions.

Methods of Penetrant Testing for Flaw Detection of Objects with a High Roughness. The degree of roughness of the tested surface imposes a rigid restriction on the use of liquid-penetrant testing methods. The higher the roughness of the surface, the more difficult the removal of excessive amounts of the indicator liquid from it before the application of the developer, since capillary forces at the microroughness–penetrant–air boundary interfere with this process. In preparing products with a high surface roughness (many welds, roughly worked surfaces, etc.) for liquid-penetrant testing, abrasive working of the tested surface by coarse grinding wheels with the use of manual grinders are used. However, the regular high-intensity regimes of grinding with cutting rates of 65 to 70 m/sec lead to a significant plastic straining of surface metal layers and to the strain and grinding of the mouths of surface defects. The resulting surface microrelief of welds after their abrasive roughing produces a substantial background glow of the penetrant in the developer layer, which is caused by numerous locally oriented surface microgrooves — the tracks of cutting of the abrasive grains. All this substantially hinders the use of visible dye penetrant testing and makes it impossible to use the most sensitive luminescent (fluoroscopic) method.

At the Institute of Applied Physics of the National Academy of Sciences of Belarus, we have proposed and are developing methods of electrochemical treatment (EChT) of welds before liquid-penetrant testing [6, 7] with the aim of diminishing the roughness of the tested surface. In EChT, we have intense dissolution of the surface layer of metal without the plastic straining of the latter, which ensures the opening of the mouths of defects and their good detectability in liquid-penetrant testing. Furthermore, the smoothing of the surface asperities and dimples of the microrelief in EChT substantially improves the ability of the penetrant to be washed away before the application of the developer, which results in the much weaker background glow in development, upgrading the testing.

The influence of abrasive treatment and EChT of welds on the detectability of defects in them with an analysis of the background glow of the tested surfaces has been investigated with a computerized setup for processing and analysis of video images. We used special steel samples with artificial defects applied in accordance with the technology developed at the Institute of Applied Physics of the National Academy of Sciences of Belarus and making it possible to obtain opening widths of 0.5 to 50 μm and depths of 100 to 600 μm.

It has been established that after the abrasive treatment, by a wheel, of the samples with artificial surface defects with opening widths of 1 to 20 μm, the latter diminish to 1 to 2 μm. Furthermore, the crack mouth is displaced sidewise by 40–80 μm in grinding-wheel velocity. After such treatment of 15Kh5M-steel samples to Rz 40–80, the areas of the indicator traces of the defects in fluoroscopic testing decrease 2.5–3 times, whereas the luminous flux diminishes 4.2–7 times. In visible dye penetrant testing, the trace areas decrease 2–3 times. Finishing by a diamond grinding wheel of the samples with defects with an opening of 1–6 μm to Ra 1–1.4 leads to a twofold decrease in the luminous fluxes and the trace areas in fluoroscopic testing.

Figure 5 gives photographs of the same sample with different local treatments of surface portions in the regions of cracks after the visible dye penetrant and fluoroscopic testing without EChT and after it. Figure 6 illustrates

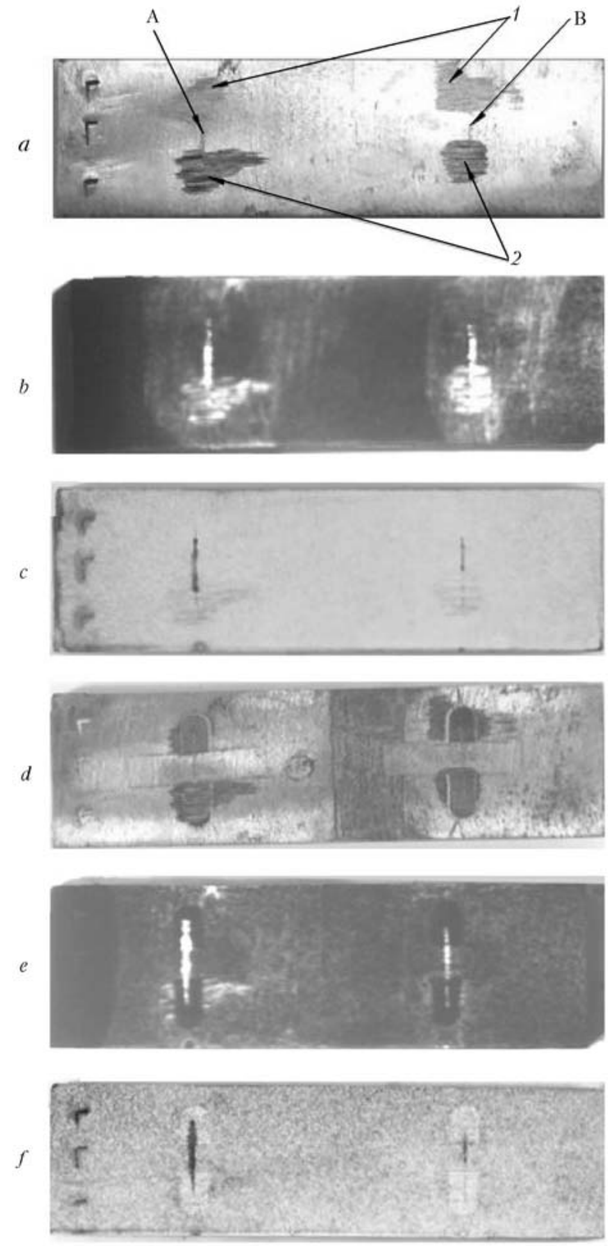

Fig. 5. Influence of EChT on the detectability of surface cracks in the sample: a) general view of the sample: A) zone of the defect with an opening of 10–12 μm and B) 5–6 μm (1) zone of finishing grinding to Ra 1–1.4 μm, 2) zone of rough grinding to Rz 40); b) fluorescent testing; c) dye-penetrant testing; d) view after the local EChT (32 A/cm^2, 3 sec); e) fluorescent testing after EChT; f) fluorescent testing after EChT.

the EChT efficiency in the case of detection of a longitudinal thermal crack in the weld. The use of EChT of the samples' surface before liquid-penetrant testing leads to an increase of 1.7–4 times in the areas and luminous fluxes of the defect traces compared to the ground surface in abrasive finishing. We have established the optimum parameters of EChT of the selected steels in an environmentally clean NaCl-based aqueous electrolyte. The range of optimum concentrations of the electrolyte was established.

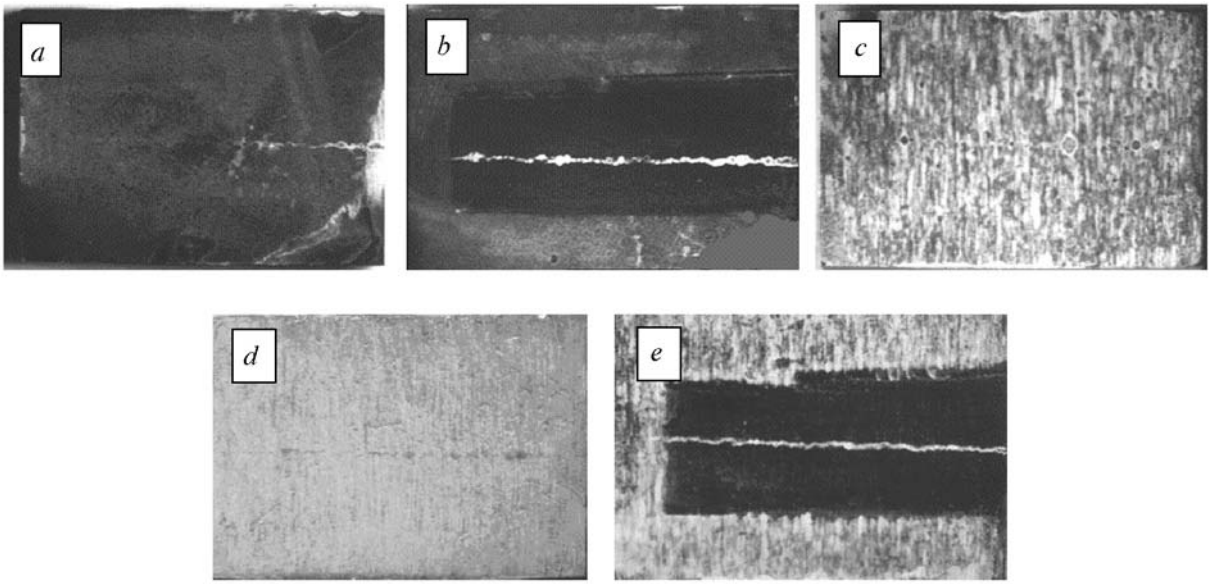

Fig. 6. Liquid-penetrant testing and EChT of the 15Kh5M-steel sample (70 × 50 × 12) with a weld and a longitudinal thermal crack: a) initial fluorescent testing of the sample before treatment (Rz 20); b) fluorescent testing of the specimen after EChT; c) fluorescent testing after rough abrasive treatment (Rz 40–80); d) dye-penetrant treatment after the rough abrasive treatment to Rz 40–80; e) fluorescent testing after rough abrasive treatment and EChT.

We have developed a new device for the EChT of welds [7]. On its implementation, a limited jet feed of the electrolyte to the working zone and the possibility of treating curvilinear surfaces, including the welds, are ensured. The EChT of welds of products under extra-workshop conditions is possible with this device.

Conclusions. The obtained scientific results have made it possible to develop and implement an efficient procedure and means of evaluating quantitatively the sensitivity of sets of flaw-detector materials and indicator liquids. A number of practical recommendations on selection of the parameters of different technological stages of penetrant testing have been proposed with the aim of increasing its sensitivity and efficiency. The technological regime of testing with blowing of the tested surface with warm air, in which not only the duration of the development stage decreases by an order of magnitude but brighter and higher-contrast indicator patterns of the detected defects are obtained as well, has been developed. As a result of an analysis of the influence of different forms of treatment of the tested surface on the detectability of cracks, it has been shown that in certain regimes, EChT first makes it possible to extend the applicability of the methods of fluorescent penetrant testing to objects with a substantially high roughness (welds, etc.). Implementation of the performed developments ensures the possibility of testing welds fluoroscopically and a substantial upgrading of the commonly used dye-penetrant method.

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