Janusz Czuchryj, Katarzyna Hyc

# Dye-penetrant method assessment of size of surface discontinuities in products made of carbon structural steel

## Introduction

While manufacturing industrial products, it is assumed that the type, number, and size of discontinuities (imperfections) occurring in such products should be at a level which is acceptable for their recipient, i.e. possibly the lowest. In order to achieve this goal one uses many various non-destructive tests. Among these is a liquid-penetrant inspection method, rated as one of the oldest and most commonly applied in industry.

The liquid-penetrant inspection makes it possible to discover solely surface discontinuities (e.g. cracks, incomplete surface fusions, no joint penetration in welded joints, porosity, etc.). The possibility of estimating the size of such discontinuities may facilitate the decision-making process whether to accept a tested product for operation or repair it. Due to the character of the method (discontinuity visualisation is most often obtained in the form of a red or shining indication (Fig. 1) [1]), it can only be made on the basis of the measurement of an indication being formed. Its dimensions are proportional to the size (cross-section, depth, volume) of an imperfection present [2].

For this reason, research has been undertaken to define the dependence between the size of an indication and the time of its development in the function of the size of a discontinuity. Such a dependence should make it possible to estimate the size, and more importantly, the depth of a surfacing discontinuity. This should be useful in the technical diagnostics of a product tested by means of the dye-penetrant method.

## Test samples

In order to determine dependences which enable the assessment of the depth of discontinuities detected by means of the dye-penetrant inspection, it was necessary to use the simulation of such discontinuities in the form of non-passthrough openings made in carbon structural steel plates St3S (S235). In order to optimise the liquid-penetrant inspection as well as for the sake of the accuracy of in-

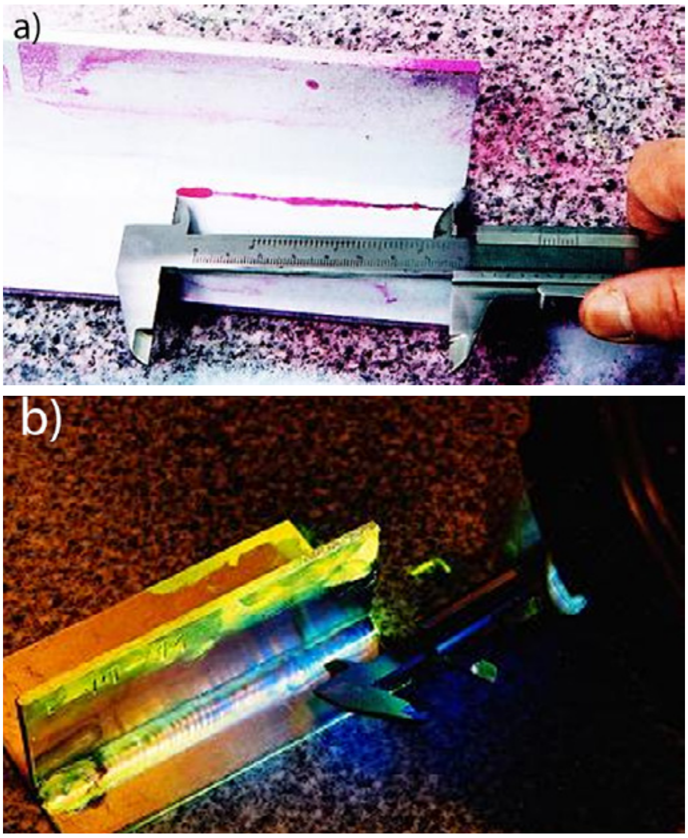


Fig. 1. Indications obtained during liquid-penetrant inspection of welded joint:
a) dye-penetrant method (observation of surface tested in natural light);b) fluorescent method (observation of surface tested at UV-A radiation)

mgr inż. Janusz Czuchryj, mgr inż. Katarzyna Hyc – Instytut Spawalnictwa, Ośrodek Kształcenia i Nadzoru Spawalniczego /Centre for Education and Welding Supervision/

Table 1. Nominal dimensions of openings in plates tested using the liquid-penetrant method.

| No. | Plate designation | Opening designation | Nominal dimensions of openings | | |
|---|---|---|---|---|---|
| | | | Diameter [mm] | Depth [mm] | Volume [mm$^3$]$^{1)}$ |
| 1 | I | 1 | 0.50 | 0.50 | 0.108 |
| 2 | | 2 | 0.75 | | 0.252 |
| 3 | | 3 | 1.00 | | 0.47 |
| 4 | II | 1 | 1.25 | | 0.759 |
| 5 | | 2 | 1.50 | | 1.146 |
| 6 | | 3 | 1.75 | | 1.607 |
| 7 | III | 1 | 0.50 | 0.75 | 0.157 |
| 8 | | 2 | 0.75 | | 0.362 |
| 9 | | 3 | 1.00 | | 0.667 |
| 10 | IV | 1 | 1.25 | | 1.066 |
| 11 | | 2 | 1.50 | | 1.587 |
| 12 | | 3 | 1.75 | | 2.208 |
| 13 | V | 1 | 0.50 | 1.00 | 0.206 |
| 14 | | 2 | 0.75 | | 0.472 |
| 15 | | 3 | 1.00 | | 0.863 |
| 16 | VI | 1 | 1.25 | | 1.373 |
| 17 | | 2 | 1.50 | | 2.029 |
| 18 | | 3 | 1.75 | | 2.809 |
| 19 | VII | 1 | 0.50 | 1.25 | 0.255 |
| 20 | | 2 | 0.75 | | 0.583 |
| 21 | | 3 | 1.00 | | 1.059 |
| 22 | VIII | 1 | 1.25 | | 1.679 |
| 23 | | 2 | 1.50 | | 2.471 |
| 24 | | 3 | 1.75 | | 3.41 |
| 25 | IX | 1 | 0.50 | 1.50 | 0.304 |
| 26 | | 2 | 0.75 | | 0.693 |
| 27 | | 3 | 1.00 | | 1.255 |
| 28 | X | 1 | 1.25 | | 1.986 |
| 29 | | 2 | 1.50 | | 2.912 |
| 30 | | 3 | 1.75 | | 4.011 |
| 31 | XI | 1 | 0.50 | 1.75 | 0.353 |
| 32 | | 2 | 0.75 | | 0.803 |
| 33 | | 3 | 1.00 | | 1.452 |
| 34 | XII | 1 | 1.25 | | 2.292 |
| 35 | | 2 | 1.50 | | 3.354 |
| 36 | | 3 | 1.75 | | |

1) During the calculation the volume of the cone of the drill end was taken into consideration

Note: With reference to discontinuity (welding imperfection) one should apply the term 'height'; however, for communication purposes this article uses the term 'depth'.

dications, only 3 openings were made in each plate. The shape and dimensions of the test plates are presented in Figure 2, whereas the nominal dimensions of the openings are presented in Table 1.

After machining, the plates were thoroughly cleaned, and the remains left by the machining process were removed, and the surface to be tested was degreased in an ultrasonic washer using extraction naphtha and solvent-based remover. Once cleaned, the plates were dried using an air jet under pressure at a temperature of approximately 20ºC.

## Testing aerosols, equipment, and conditions

The liquid-penetrant inspection of the plates with simulated discontinuities involved the use of a set of testing aerosols designated, following the requirements of standard PN-EN 571-1, as EN 571-1 IICd-2, type "Diffu - Therm", manufactured by H. Klumpf Techn. Chemie KG D-45699 Herten (Fig. 3).

The aerosols used in the tests were as follows:

• penetrant – red colour, type BDR, lot no.: 2112, filling date: 08/2010;
• remover – type BDR-S, lot no.: 7010, filling date: 05/2011;
• developer – type BEA, lot no.: 2313, filling date: 04/ 2011;

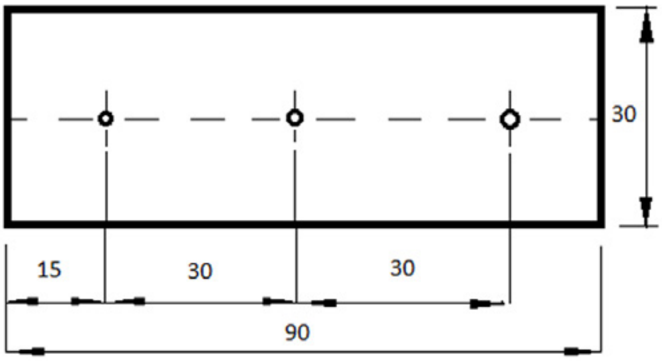


Fig. 2. Shape and dimensions of plates with openings tested using the dye-penetrant method. Thickness of material: 4mm

- guarantee period – 5 years;
- no chlorine or sulphur compounds in the chemical composition.


Fig. 3. Set of aerosols "Diffu - Therm" used in the liquid -penetrant inspection of plates with discontinuities

The tests involved the use of the following measuring equipment and materials:

- caliper with measurement accuracy of 0.02 mm;
- thermometer/hygrometer, model 303, manufactured by the company "Emerbi";
- luxmeter – type LX 105 manufactured by the company "LX Lutron";
- magnifying glass (4 x);
- non-shredding fabric.

The liquid-penetrant inspections of the plates were conducted in the following conditions:

- temperature of tested surface – 22ºC;
- ambient humidity – 20%;
- penetration time – 15 min.;
- development time – 30 min.;
- illuminance of tested surface – 1100 lx;
- observation distance –10-30 cm;
- observation angle – from 60 to 90º.

## Conducted inspections and obtained results

The liquid-penetrant inspections of the samples with openings were carried out using the dye-penetrant method following the requirements of standard PN-EN 571-1. The measurements of indications were conducted after 2, 5, 10, 15, 20, 25 and 30 minutes. The measurements carried out at the initial stage of the appearance of indications aimed at more accurate determination of the dependence being the subject of this work and the assessment of the dynamics of the formation of the indications. The maximum adopted indication development time met the requirements of standard PN-EN 571-1, according to which it should be contained within a 10-30 minute range. The sample during the inspection is presented in Figure 4.

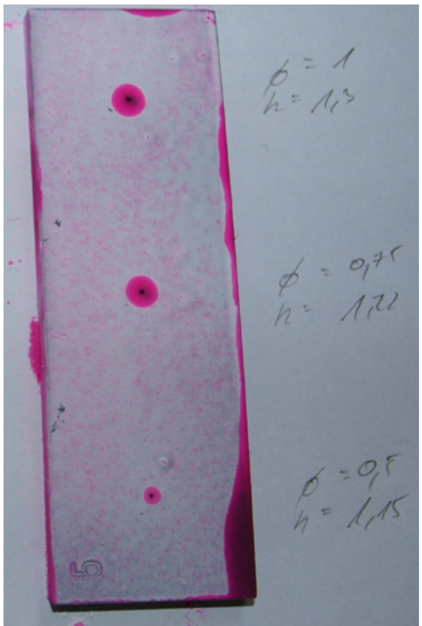


Fig. 4 Sample with discontinuities during dye-penetrant inspection

The test results, in the form of the measurements of the greatest indication values, are presented in Table 2.

## Analysis of inspection results

The values of penetrant indications from simulated discontinuities measured at measurement points (Table 2) are presented in the graphic form in Figures 5 – 10.

Table2. Results of liquid-penetrant inspections (measurement of indication sizes) for openings with various diameters and various depths in relation to their development time.

| Nominal opening diameter Φ [mm] | 0.50 | 0.75 | 1.00 | 1.25 | 1.50 | 1.75 |
|---|---|---|---|---|---|---|
| Development time [min] | SIZE OF INDICATION [mm] | | | | | |
| h = 0.50 mm 1) | | | | | | |
| 2 | 3.26 | 3.63 | 4.63 | 5.13 | 5.20 | 5.69 |
| 5 | 3.63 | 4.07 | 4.97 | 5.67 | 5.90 | 6.47 |
| 10 | 3.63 | 4.10 | 5.07 | 5.75 | 6.06 | 6.56 |
| 15 | 3.66 | 4.10 | 5.10 | 5.80 | 6.06 | 6.80 |
| 20 | 3.70 | 4.20 | 5.13 | 5.83 | 6.20 | 6.83 |
| 25 | 3.70 | 4.20 | 5.13 | 5.93 | 6.20 | 6.83 |
| 30 | 3.73 | 4.20 | 5.13 | 5.93 | 6.20 | 6.83 |
| h = 0.75 mm 1) | | | | | | |
| 2 | 3.42 | 5.16 | 6.07 | 5.23 | 6.36 | 7.47 |
| 5 | 4.03 | 5.87 | 6.93 | 6.83 | 7.47 | 7.63 |
| 10 | 4.07 | 6.00 | 7.13 | 7.50 | 8.06 | 8.46 |
| 15 | 4.07 | 6.13 | 7.17 | 7.70 | 8.23 | 8.80 |
| 20 | 4.13 | 6.23 | 7.30 | 7.87 | 8.30 | 8.80 |
| 25 | 4.13 | 6.23 | 7.30 | 8.20 | 8.47 | 8.96 |
| 30 | 4.13 | 6.23 | 7.30 | 8.20 | 8.47 | 8.96 |
| h = 1.00 mm 1) | | | | | | |
| 2 | 3 | 4.93 | 5.4 | 6.43 | 6.88 | 7.67 |
| 5 | 3.77 | 6.8 | 7.3 | 7.95 | 8.99 | 9.48 |
| 10 | 3.9 | 7.06 | 8.06 | 8.8 | 10.12 | 10.8 |
| 15 | 3.93 | 7.27 | 8.3 | 9 | 10.83 | 11.06 |
| 20 | 3.93 | 7.36 | 8.3 | 9.17 | 11.26 | 11.4 |
| 25 | 3.93 | 7.36 | 8.63 | 9.17 | 11.58 | 11.6 |
| 30 | 3.93 | 7.36 | 8.63 | 9.17 | 11.58 | 11.73 |
| h = 1.25 mm 1) | | | | | | |
| 2 | 2.43 | 4.47 | 5.5 | 6.1 | 7.32 | 8.6 |
| 5 | 3.4 | 4.83 | 6.53 | 8.3 | 9.93 | 10.7 |
| 10 | 3.45 | 5.2 | 7.2 | 10 | 11.7 | 11.97 |
| 15 | 3.48 | 5.37 | 7.7 | 10.9 | 12.97 | 12.58 |
| 20 | 3.5 | 5.37 | 7.93 | 11.17 | 13.76 | 13.37 |
| 25 | 3.5 | 5.37 | 8.7 | 11.9 | 14.7 | 14.2 |
| 30 | 3.5 | 5.37 | 8.73 | 12.03 | 14.9 | 14.3 |
| h = 1.50 mm 1) | | | | | | |
| 2 | 3.28 | 4.63 | 6.7 | 6.47 | 7.6 | 8.73 |
| 5 | 4.3 | 5.7 | 7.6 | 8.63 | 9.67 | 10.45 |
| 10 | 4.56 | 6 | 8.2 | 10.63 | 10.2 | 12.2 |
| 15 | 4.53 | 6.43 | 8.87 | 11.49 | 11.66 | 13.47 |
| 20 | 4.73 | 6.73 | 9.33 | 12.33 | 12.46 | 14.63 |
| 25 | 4.8 | 6.73 | 9.33 | 12.5 | 12.73 | 15.29 |
| 30 | 4.8 | 6.73 | 9.33 | 12.5 | 13.3 | 16.16 |

As can be seen in the figures, the coordinates of individual points are determined by the measured time of development and the measured size of an indication. Points of various coordinates but related to the same size of discontinuity (discontinuity of the same diameter and depth) are connected with sections designating thus a broken line, illustrating the course of the dependence being the subject of this work.

The analysis of the courses of broken lines reveals that an increase in the diameter of a discontinuity is, in each case, accompanied by an increase in the maximum size of the indication obtained from this discontinuity. Such a result is consistent with expectations. Nevertheless, it is worth mentioning that the courses of individual lines are characterised by certain tendencies. At the initial phase of the generation of indications (a development time from 0 to 5 minutes) the broken lines are characterised by a significant inclination in relation to the axis of the development time. This fact reflects the high dynamics of the increase in indications and concerns almost all observed cases. In the range of a development time from 5 to 30 minutes, the broken lines representing the indications from a disconti-

| Nominal opening diameter Φ [mm] | 0.50 | 0.75 | 1.00 | 1.25 | 1.50 | 1.75 |
|---|---|---|---|---|---|---|
| Development time [min] | SIZE OF INDICATION [mm] | | | | | |
| h = 1.75 mm [1)] | | | | | | |
| 2 | 2.43 | 3.43 | 5.93 | 6.2 | 5.47 | 7.9 |
| 5 | 2.93 | 4.5 | 6.95 | 8.03 | 7.8 | 9.63 |
| 10 | 3.16 | 5.57 | 8.67 | 9 | 9.23 | 11.43 |
| 15 | 3.36 | 6.06 | 9.5 | 10.37 | 10.77 | 12.99 |
| 20 | 3.36 | 6.13 | 10.03 | 11.43 | 11.87 | 14.06 |
| 25 | 3.36 | 6.13 | 10.16 | 12 | 13.03 | 15 |
| 30 | 3.36 | 6.13 | 10.3 | 13 | 13.5 | 15.56 |

[1)] h - nominal opening depth

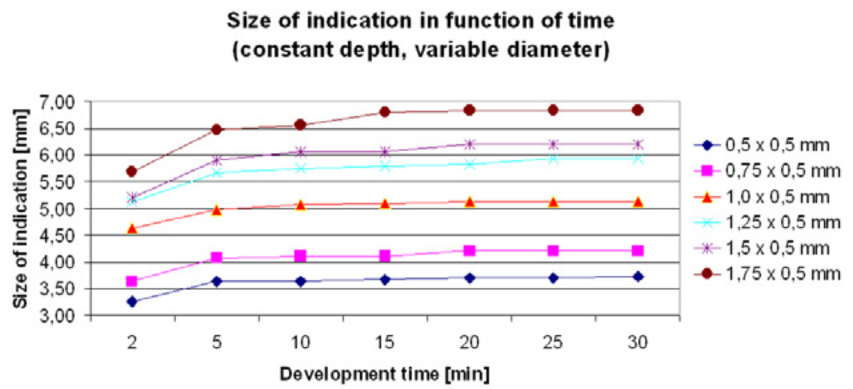


Fig. 5. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 0.50 mm and various diameters

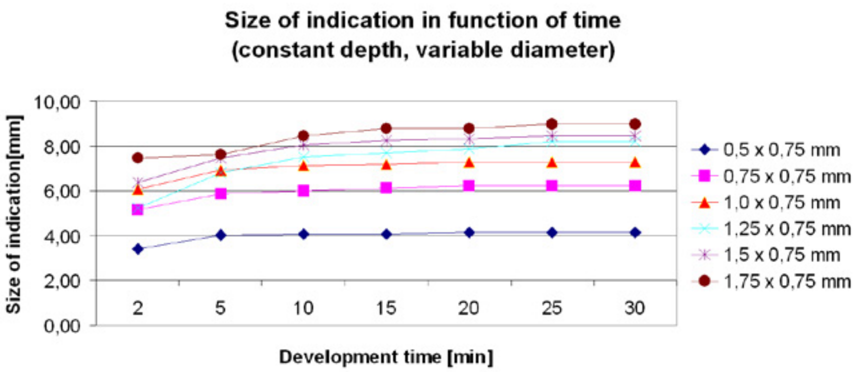


Fig. 6. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 0.75 mm and various diameters

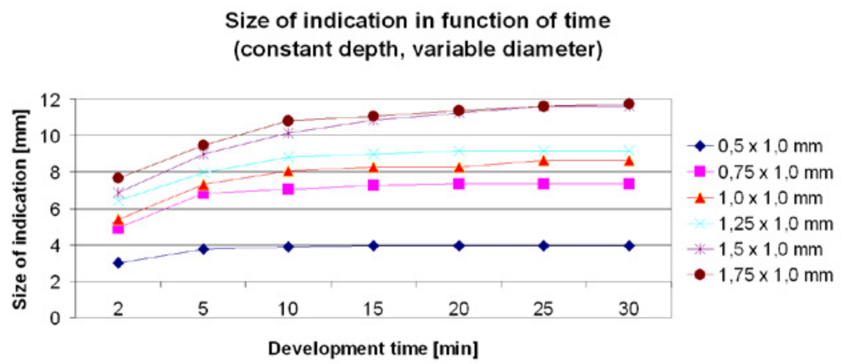


Fig. 7. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 1.00 mm and various diameters

nuity with a small depth (h = 0.5 – 1.0 mm), quickly become parallel or almost parallel to the axis of a development time. This reflects the easy stabilisation of the maximum size of an indication. Quite different observations were made for discontinuities of greater sizes (h = 1.25 – 1.75 mm and Φ = 1.25 – 1.75 mm). In these cases the stabilisation of the maximum size of an indication occurs at a later phase of the development process or does not occur at all (e.g. the broken lines presented in Figures 9-10 show a rising tendency even at the maximum development time). One can thus observe the lack of stabilisations of measured indications. This leads to the conclusion that for unalloyed structural steels the development time of indications from surface non-compliances during dye penetrant tests should be longer than specified in the guidelines of standard PN -EN 571-1. Figures 6 and 8-10 also present the “interleaving” of some broken lines. For instance, in the area of the development time from 5 to10 minutes, one can observe the intersections of the lines designating discontinuities Φ 1.0 x 0.75 mm and Φ 1.25 x 0.75 mm (Fig. 6), Φ 1.25 x 1.5 mm and Φ 1.5 x 1.5 mm (Fig. 9) and Φ 1.25 x 1.75 mm and Φ 1.5 x 1.75 mm (Fig. 10). In turn, in Figure 8 one can

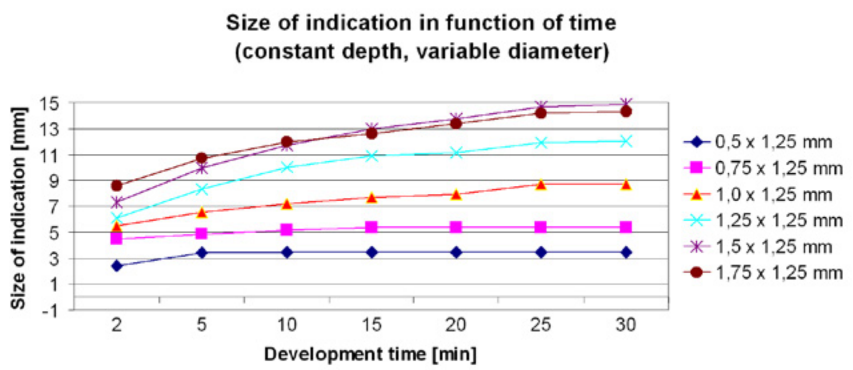


Fig. 8. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 1.25 mm and various diameters

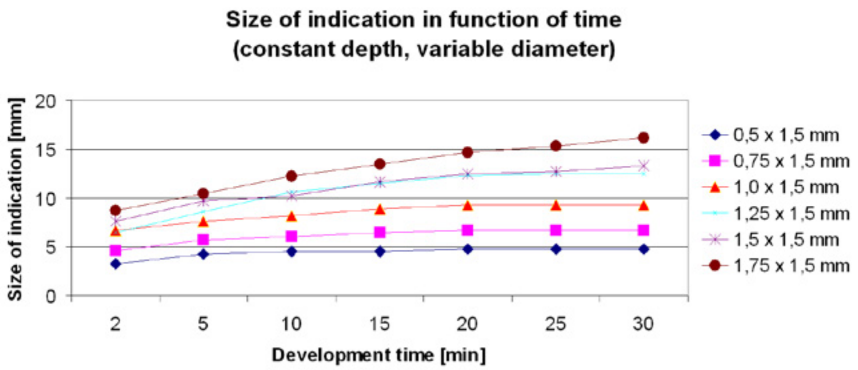


Fig. 9. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 1.50 mm and various diameters

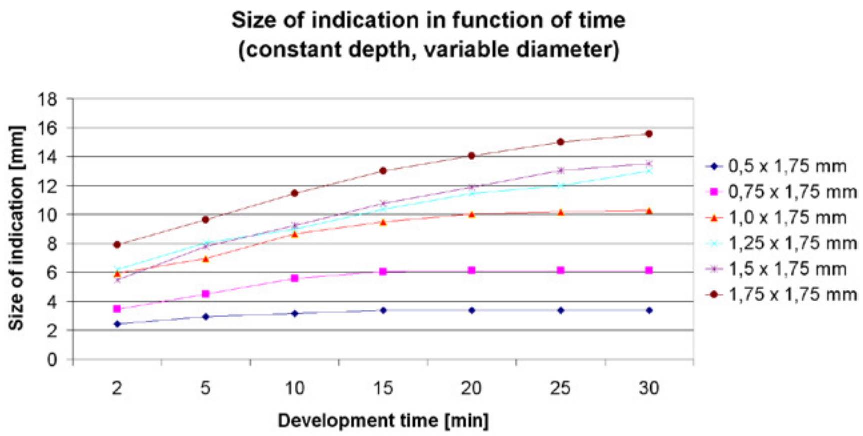


Fig. 10. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 1.75 mm and various diameters

observe the intersection of the broken lines in the area of 10-15 minutes of a development time concerning discontinuities Φ 1.5 x 1.25 mm and Φ 1.75 x 1.25 mm. In the last case the line of the discontinuity of the greater diameter (Φ 1.75) reveals the maximum sizes of indications smaller that the line of the discontinuity of the smaller diameter (Φ 1.5). Such an observation is inconsistent with expectations. One should, however, take into consideration the fact that the liquid-penetrant test consists of a number of phases to be carried out. Each of these phases, due to testing sensitivity, should be conducted with a lot of attention paid to details. Each negligence in the course of the process decreases the sensitivity of the test and affects its final result. Bearing that in mind, one can easily explain inaccuracies in the courses of some broken lines revealed in Figures 6 and 8-10

The tests results were subjected to further analysis. The dependences between the time of development and the size of an indication were verified for the cases when the diameter ”Φ” of the opening simulating a discontinuity is constant and the depth “h” of the opening changes. Broken lines illustrating the dependences were determined in the same manner as described before. Selected analysis results are presented in Figure 11.

As one can see in Figure 11, some broken lines lie below expected values or intersect the lines representing other sizes of simulated discontinuities. If compared with the previously presented dependences (Fig. 6 - 10) they are characterised by greater disorder. This fact can be easily explained. Making a given size of the diameter of an opening is burdened by a significantly smaller error than obtaining a given depth. For this reason the dimension of the depth of an opening is characterised by a much greater spread of

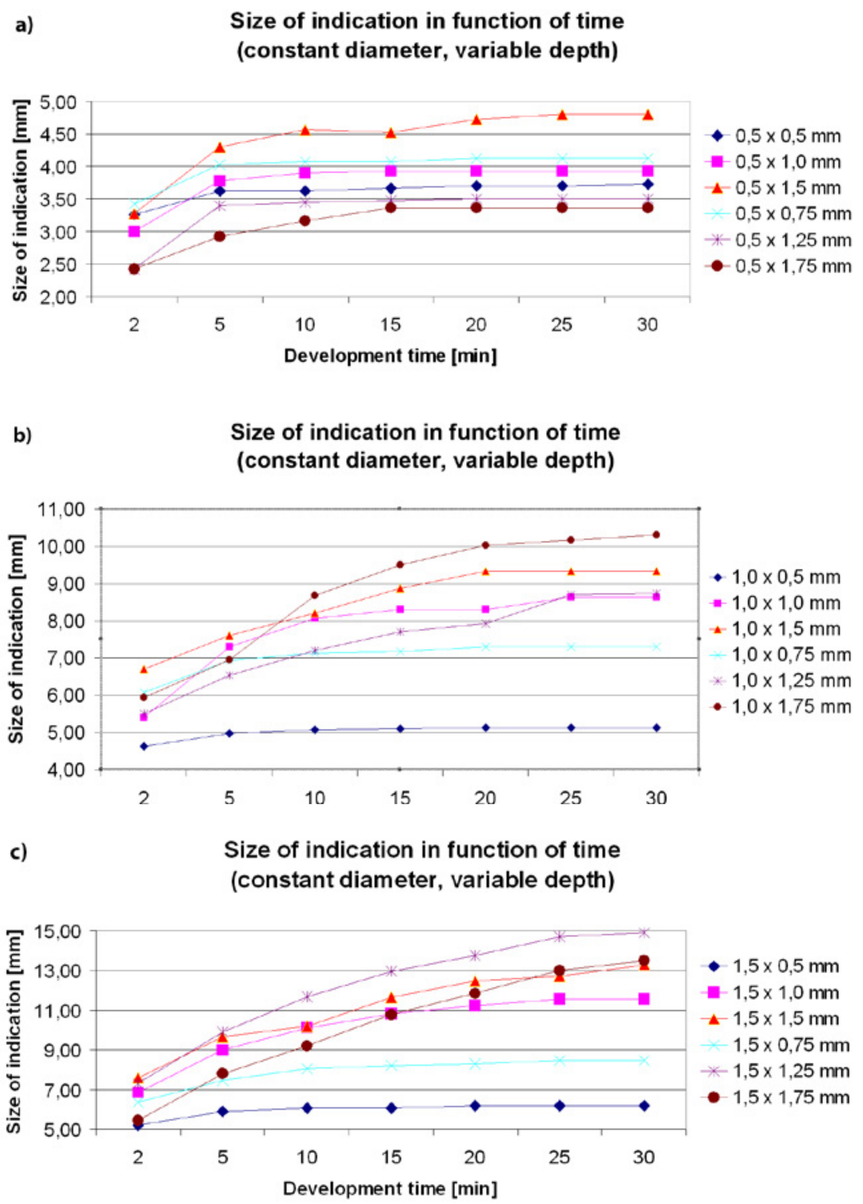


Fig. 11. Selected results of measurements of sizes of penetrant indications in function of development time of samples with openings of various depth and nominal diameter of:
a) 0.5 mm, b) 1.0 mm and c) 1.5 mm

workmanship than its diameter. This is why the presented figures contain differences which are not to be observed if a diameter is adopted as a reference level. In order to minimise the described errors one should increase the gradient of observed sizes. For this reason, while carrying out the analysis of the impact of the depth of an opening on the size of a penetrant indication it was necessary to adopt the gradient of the depth of an opening equal to 0.5 mm instead of the gradient of 0.25 mm. The analysis results are presented in Figure 12.

As can be seen in Figure 12, the values enabling the determination of broken lines (taking into consideration the depth of a discontinuity as a quantity subject to observation), in the corrected analytical approach, meet the expectations of the experiment and can be regarded as reliable.

On the basis of the determined dependence between the size of an indication and a development time, in the function of the size of a discontinuity, it has become possible to estimate the depth of this discontinuity. This, of course, refers to discontinuities in the form of surface porosity. A general procedure in this scope includes the following:

• measurement of a pore diameter by means of a device of accuracy of at least 0.1 mm;

• carrying out liquid-penetrant inspection following the requirements of standard PN-EN 571-1;

• providing observation conditions following the requirements of standard PN-EN ISO 3059;

• measurement of the maximum size of an obtained indication after the passage of the adopted development time;

• determination of a point of the following coordinates: the size of an indication – development time, in such a manner, that the point lies on the broken line corresponding to the measured diameter of a pore or as close to this line as possible;

• reading out the estimated depth of a pore, designating the previously determined broken line.

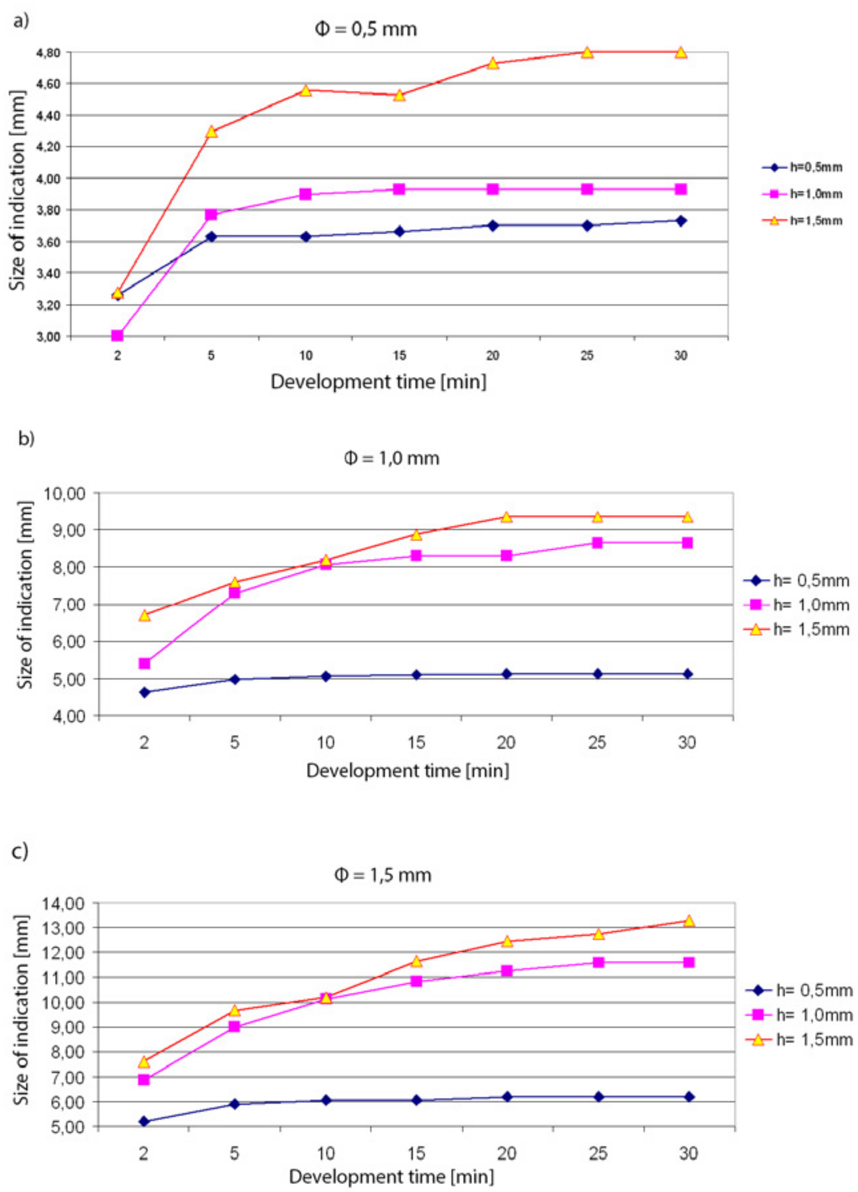


Fig. 12. Results of measurements of sizes of penetrant indications in the function of development time of samples with openings of nominal depth "h" of 0.5 mm, 1.0 mm and 1.5 mm and nominal diameter "Φ" of : a) 0.5 mm, b) 1.0 mm, c) 1.5 mm

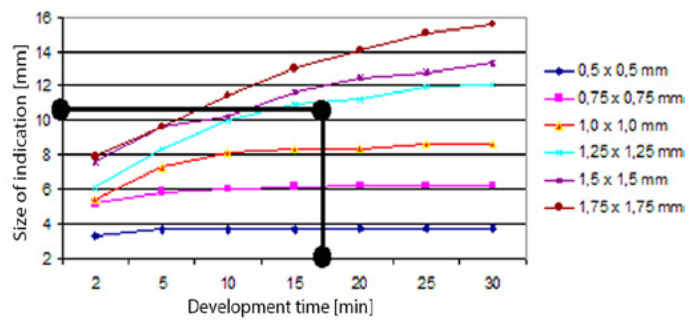


Fig. 13. Example of determination of estimated depth of pores; Measured data: pore diameter – 1.25 mm, the size of an indication - 11 mm, development time -17 minutes. As can be seen, the point of the intersection of the coordinates 10.5 mm and 17 min. lies slightly below the broken line representing the pore of the dimensions of Φ 1.25 x 1.25 mm. It is therefore possible to conclude that the depth of the pore of the diameter of 1.2 mm amounts to approximately 1.2 mm.

An example of how to determine the estimated depth of pores is presented in Figure 13. For the sake of clarity only selected broken lines have been used.

## Summary and conclusions

The conducted liquid-penetrant inspections of the samples with openings simulating discontinuities (pores) revealed that the undertaken target of the research had been reached. The determined dependences (the size of an indication – development time, in the function of the size of a discontinuity) make it possible to estimate the depth of discontinuities in products made of unalloyed structural steels. Such information should facilitate the decision whether to accept a given product for operation or repair it. It should also be mentioned that in some cases, after the passage of the maximum development time, it was possible to observe the lack of stabilisation of the measured liquid-penetrant indications. This fact suggests that the time should be longer than specified in standard PN-EN 571-1. On the basis of the estimated depth of a discontinuity, one may also make conclusions about possible leaks of welded joints, particularly of joints with fillet welds. This can be of particular importance in relation to some products (e.g. storage tanks). However, it is necessary to extend the range of research and include discontinuities of greater depths.

On the basis of the conducted liquid-penetrant inspections it was possible to determine dependences in the form of broken lines. This is the first approximation of real courses. In order to obtain test results closer to reality, it is necessary to carry out a greater number of measurements. More measurements are required for their reliable statistical analysis.

On the basis of the conducted tests it was possible to formulate the following conclusions:

- conducted dye penetrant inspections made it possible to achieve the purpose of the research work consisting in obtaining a possibility of estimating depths of surface discontinuities in the form of porosity present in products made of unalloyed structural steels grade S235;
- the analysis of the results of the conducted penetrant inspections reveals that the maximum development time of indications on surfaces of unalloyed structural steels grade S235 should be longer than specified in standard PN-EN 571-1;
- on the basis of the conducted tests and their results one can estimate leaks of welded joins, particularly of joints with fillet welds;
- in order to increase the accuracy and usability of the obtained test results in the industrial practice, it is necessary to increase the number and extend the scope of tests;
- one should consider, taking into account the purpose of work, the possibility and advisability of using fluorescent penetrant tests instead of dye penetrant inspections.

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## Reference standards:


- PN-EN 571-1 „Badania nieniszczące - Badania penetracyjne – Zasady ogólne”.
- PN-EN ISO 3452-2 „Badania nieniszczące - Badania penetracyjne - Część 2: Badania materiałów penetracyjnych”.
- PN-EN ISO 3059 „Badania nieniszczące – Badania penetracyjne i badania magnetyczno-proszkowe – Warunki obserwacji”