Janusz Czuchryj, Paweł Irek

Dye-Penetrant Method Assessment of the Size of Pores in Welded Joints Made of High-Alloy Steel

Abstract: The article describes the penetrant tests carried out on X5CrNi18-10 high-alloy steel provided with artificial discontinuities, i.e. pores (drilled openings). The tests involved the measurements of indication sizes depending on the time of development and various diameters and depths of openings. The correlations determined enable estimating the depth of pores in welded products made of high-alloy steels. The information obtained should enable decision-making concerning the acceptance of a product for operation or the necessity of repairing it. The tests also involved the determination of an optimum indication development time for high-alloy steels. The article is the continuation of the research works published in editions nos. 4/2012 and 4/2014 of this magazine.

Keywords: non-destructive testing, dye-penetrant method, X5CrNi18-10 steel

Introduction

The assessment of welded joint properties has become a key element of quality control in welding engineering. Welding is a special production process, which means that process-related imperfections can be disclosed only during the operation of welded products. For this reason, welding should always be performed by qualified personnel and welding process parameters should be controlled and monitored on a non-stop basis. Deviations from a proper welding technology can lead to imperfections formed in welded joints. This, in turn, can result in serious failures of structures and significant material losses or can cause risk to human life. Thus, the type, amount and size of imperfections in joints should be as low as possible. To reach this goal, testers can rely on a vast number of various non-destructive testing methods (NDT), one of which, commonly used in production practice, is penetrant testing. Penetrant testing belongs to surface NDT methods enabling solely the detection of welding imperfections reaching the surface of a welded joint (Fig. 1) [1, 2].

a) b)

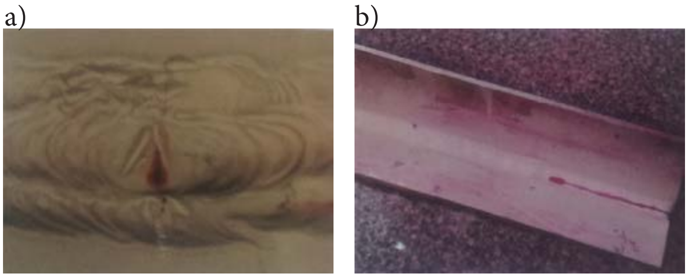

Fig. 1. Indications obtained by means of penetrant testing using a dye-penetrant method: a) non-linear indication, b) linear indication

Surface imperfections include, among other things, porosity [3]. The depth of pores can be significant, and as regards the active life of a joint, leaktightness and operational fracture risk is highly undesirable. For this reason, the

mgr. inż. Janusz Czuchryj (MSc Eng.), mgr inż. Paweł Irek (MSc Eng.) – Instytut Spawalnictwa, Centre for Education and Welding Supervision

possibility of estimating the size of pores is of paramount practical importance as it may facilitate decision-making concerning the acceptance of a given product for operation or the necessity of repairing it.

The depth of pores can be assessed only on the basis of penetrant indication size measurements. This requires the determination of the correlation between the size of indications and the size of pores, usually in the function of indication development time, for specific groups of structural materials. Previous works [4, 5] have enabled the assessment of the size of pores in welded joints made of carbon structural steel and of aluminium. This articles contains a description of tests and measurements involving high-alloy steel. The information obtained in the tests will be useful in the technical diagnostics of welded products tested using dye-penetrant methods.

Test Pieces

In order to determine dependences enabling the assessment of the depth (height) of pores it was necessary to use simulations of such discontinuities in the form of non-passthrough openings made in 4 mm thick X5CrNi18-10 steel plates (Fig. 2).

In order to optimise the penetrant test (among other things, the measurement accuracy of indications), only 3 openings were made in each plate. The nominal dimensions of openings simulating pores are presented in Table 1.

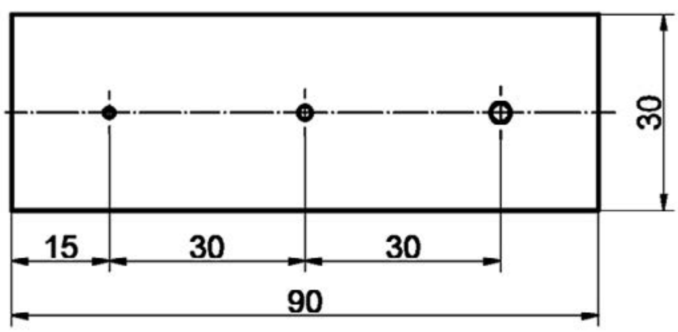

Fig. 2. Shape and dimensions of 4 mm thick X5CrNi18-10 high-alloy steel plates for dye-penetrant tests

Table 1. Designation and nominal dimensions of openings in high-alloy steel plates for penetrant tests

No.	Plate designation	Opening designation	Nominal dimensions of openings	
			diameter [mm]	depth [mm][1)]
1	I	1	0.50	0.50
2		2	0.75	
3		3	1.00	
4	II	1	1.25	
5		2	1.50	
6		3	1.75	
7	III	1	0.50	0.75
8		2	0.75	
9		3	1.00	
10	IV	1	1.25	
11		2	1.50	
12		3	1.75	
13	V	1	0.50	1.00
14		2	0.75	
15		3	1.00	
16	VI	1	1.25	
17		2	1.50	
18		3	1.75	
19	VII	1	0.50	1.25
20		2	0.75	
21		3	1.00	
22	VIII	1	1.25	
23		2	1.50	
24		3	1.75	
25	IX	1	0.50	1.50
26		2	0.75	
27		3	1.00	
28	X	1	1.25	
29		2	1.50	
30		3	1.75	
31	XI	1	0.50	1.75
32		2	0.75	
33		3	1.00	
34	XII	1	1.25	
35		2	1.50	
36		3	1.75	

[1)] With reference to discontinuities (welding imperfections) the term 'height' should be applied; however, for communication purposes this article uses the term 'depth'

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 20°C.

Testing Aerosols, Equipment and Conditions

The penetrant tests of the plates with simulated pores involved the use of a set of testing aerosols designated, following the requirements of standard PN-EN ISO 3452-1, as II Ce-2, type "Diffu-Therm", manufactured by H. Klumpf Techn. Chemie KG D-45699 Herten (Fig. 3).

Fig. 3. Set of aerosols "Diffu - Therm" used in the penetrant tests of plates with simulated pores

The aerosols used in the tests were as follows:
- penetrant – red colour, type BDR-L, lot no.: 21 16, filling date: 09/2013,
- remover – type BRE, lot no.: 22 16, filling date: 02/2013,
- developer – type BEA, lot no.: 23 16, filling date: 06/2013,
- guarantee period – 2 years,
- no chlorine or sulphur compounds in the chemical composition.

The tests involved the use of the following measuring equipment:
- luxmeter – type LX 105 manufactured by the company "Lx Lutron";
- thermometer/hygrometer, model 303;
- caliper with measurement accuracy of 0.02 mm;
- workshop magnifying glass (4x);
- non-shredding fabric.

The penetrant tests of the plates were conducted in the following conditions:
- temperature of tested surface – 220°C,
- ambient humidity – 23%,
- penetration time – 15 minutes,
- development time – 60 minutes,
- illuminance of tested surface – 584 lx,
- observation distance –10-30 cm,
- observation angle – from 60 to 90°.

Conducted Tests and Obtained Results

The liquid-penetrant inspections of the samples with simulated pores were carried out using the dye-penetrant method following the requirements of standard PN-EN ISO 3452-1. The measurements of indications were conducted after 2, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55 and 60 minutes. The measurements carried out at the initial stage of the appearance of indications were aimed at a more accurate determination of the correlation 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 ISO 3452-1, according to which it should be contained within a range of 10-30 minutes. The development time for austenitic steel was extended in accordance with data found in related reference publications. The samples with developed indications are presented in Figure 4 [2].

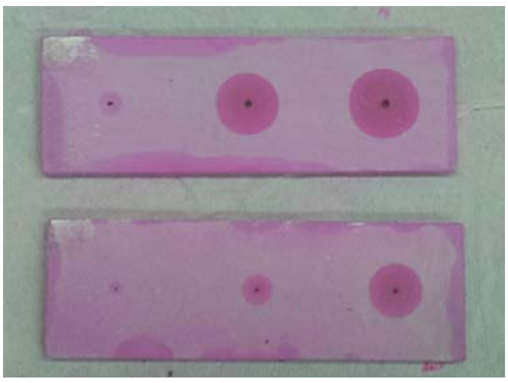

Fig. 4. Samples with developed indications of simulated pores

Table 2. Results of penetrant tests (measurements of indication sizes) for openings (pore simulations) with various diameters and various depths in relation to their development time ([1]) h – nominal opening depth)

Nominal opening diameter, ø, [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	2.52	3.44	5.38	4.42	5.88	6.42
5	4.34	5.26	5.98	5.80	7.44	7.9
10	4.34	7.46	6.38	6.10	8.72	9.3
15	4.34	7.46	6.68	6.10	9.80	11.04
20	4.34	7.46	6.68	6.10	9.80	12.34
25	4.34	7.46	6.68	6.10	9.80	12.34
30	4.34	7.46	6.68	6.10	9.80	12.34
35	4.34	7.46	6.68	6.10	9.80	12.34
40	4.34	7.46	6.68	6.10	9.80	12.34
45	4.34	7.46	6.68	6.10	9.80	12.34
50	4.34	7.46	6.68	6.10	9.80	12.34
55	4.34	7.46	6.68	6.10	9.80	12.34
60	4.34	7.46	6.68	6.10	9.80	12.34
h = 0.75 mm[1)]						
2	2.94	5.18	5.32	4.84	5.08	5.32
5	5.14	6.74	7.46	6.88	7.34	7.54
10	5.14	7.56	9.68	7.8	9.4	9.28
15	5.14	7.72	10.4	8.7	11.84	10.42
20	5.14	8.2	10.4	9.02	12.16	10.42
25	5.14	8.2	10.4	9.02	12.16	10.42
30	5.14	8.2	10.4	9.02	12.16	10.42
35	5.14	8.2	10.4	9.02	12.16	10.42
40	5.14	8.2	10.4	9.02	12.16	10.42
45	5.14	8.2	10.4	9.02	12.16	10.42
50	5.14	8.2	10.4	9.02	12.16	10.42
55	5.14	8.2	10.4	9.02	12.16	10.42
60	5.14	8.2	10.4	9.02	12.16	10.42
h = 1.00 mm[1)]						
2	3.68	4.42	5.32	4.6	5.18	7.23
5	5.38	6.86	7.48	6.56	7.32	9.05
10	5.42	7.9	9.36	8.44	9.68	11.02
15	5.42	8.7	10.32	10.23	11.18	12.87
20	5.42	8.82	10.32	11.78	12.26	13.67
25	5.42	8.82	10.32	12.67	13.18	14.62
30	5.42	8.82	10.32	13.43	13.94	15
35	5.42	8.82	10.32	13.94	14.46	15.24
40	5.42	8.82	10.32	14.12	14.84	15.32
45	5.42	8.82	10.32	14.12	15	15.32
50	5.42	8.82	10.32	14.12	15	15.32
55	5.42	8.82	10.32	14.12	15	15.32
60	5.42	8.82	10.32	14.12	15	15.32

Nominal opening diameter, ø, [mm]	0.50	0.75	1.00	1.25	1.50	1.75
Development time [min]	SIZE OF INDICATION [mm]					
h = 1.25 mm[1)]						
2	3.32	4.54	5.2	6.54	6.2	6.96
5	3.9	5.12	7	8.54	8.7	9.28
10	4.1	5.14	8.42	9.88	10.14	10.66
15	4.16	5.14	8.9	11.18	11.58	11.96
20	4.16	5.14	8.9	12.02	12.62	13.18
25	4.16	5.14	8.9	12.58	13.84	14.2
30	4.16	5.14	8.9	13.52	14.24	15.28
35	4.16	5.14	8.9	14.06	14.64	15.84
40	4.16	5.14	8.9	14.06	15.02	16.38
45	4.16	5.14	8.9	14.06	15.02	16.68
50	4.16	5.14	8.9	14.06	15.02	16.8
55	4.16	5.14	8.9	14.06	15.02	16.8
60	4.16	5.14	8.9	14.06	15.02	16.8
h = 1.50 mm[1)]						
2	2.85	5	6.1	7.08	7.85	7.81
5	2.9	5.8	7.44	9.07	10.05	10.15
10	2.9	6.44	9.2	11.34	12.75	12.85
15	2.9	6.44	10	12.86	14.09	14.23
20	2.9	6.44	10.46	13.91	14.95	15.39
25	2.9	6.44	11.1	14.6	15.43	16.28
30	2.9	6.44	11.1	15.19	16.1	16.89
35	2.9	6.44	11.1	15.34	16.34	17.38
40	2.9	6.44	11.1	15.5	16.58	17.66
45	2.9	6.44	11.1	15.66	16.72	17.84
50	2.9	6.44	11.1	15.8	16.82	18.08
55	2.9	6.44	11.1	15.88	16.9	18.22
60	2.9	6.44	11.1	15.88	16.96	18.32
h = 1.75 mm[1)]						
2	2.08	4.92	5.24	4.99	7.8	7.75
5	2.92	6.32	6.42	6.39	9.24	10
10	2.92	8.16	8.16	8.26	10.92	12.65
15	2.92	9.23	8.98	9.23	12.26	14
20	2.92	10.2	9.55	10.3	13.29	14.88
25	2.92	10.2	10.1	10.3	14.18	15.4
30	2.92	10.2	10.6	10.3	14.62	16.15
35	2.92	10.2	10.6	10.3	15	16.94
40	2.92	10.2	10.6	10.3	15.1	17.68
45	2.92	10.2	10.6	10.3	15.2	18.22
50	2.92	10.2	10.6	10.3	15.3	18.46
55	2.92	10.2	10.6	10.3	15.3	18.64
60	2.92	10.2	10.6	10.3	15.3	18.8

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

Analysis of test results

The values of penetrant indications from simulated pores (Table 2) are presented in the graphic form in Figures 5-10.

As can be seen in Figures 5–10, the coordinates of individual measurement points are determined by the measured size of an indication and its development. Points of various coordinates yet concerning the same size of a surface pore (i.e. a pore of the same diameter and

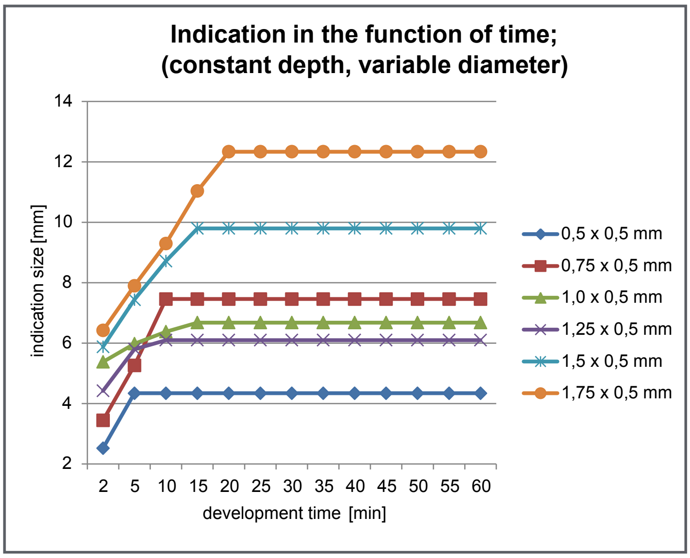

Fig. 5. Results of penetrant tests of the samples with the openings of a nominal depth of h = 0.50 mm and various diameters.

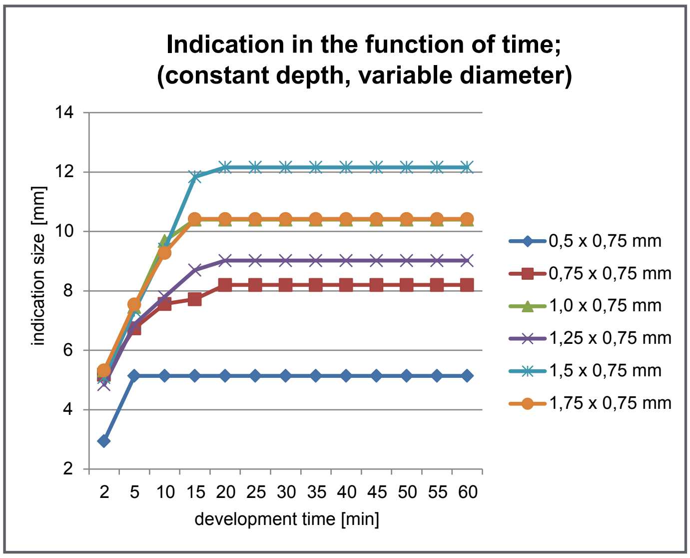

Fig. 6. Results of penetrant tests of the samples with the openings of a nominal depth of h = 0.75 mm and various diameters

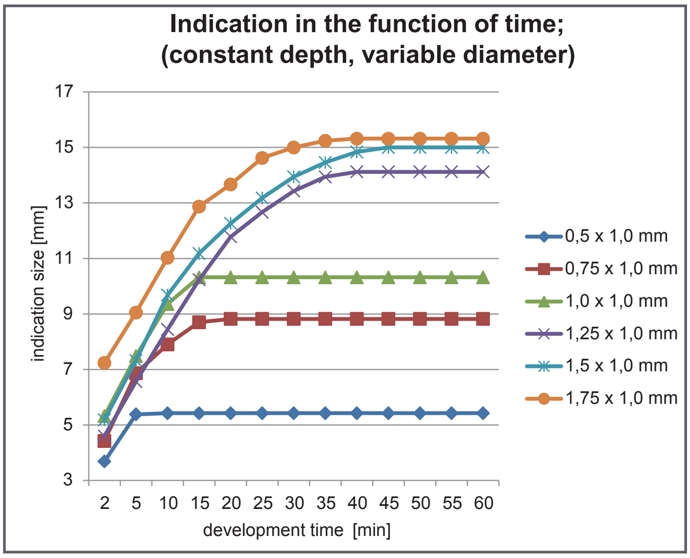

Fig. 7. Results of penetrant tests of the samples with the openings of a nominal depth of h = 1.0 mm and various diameters

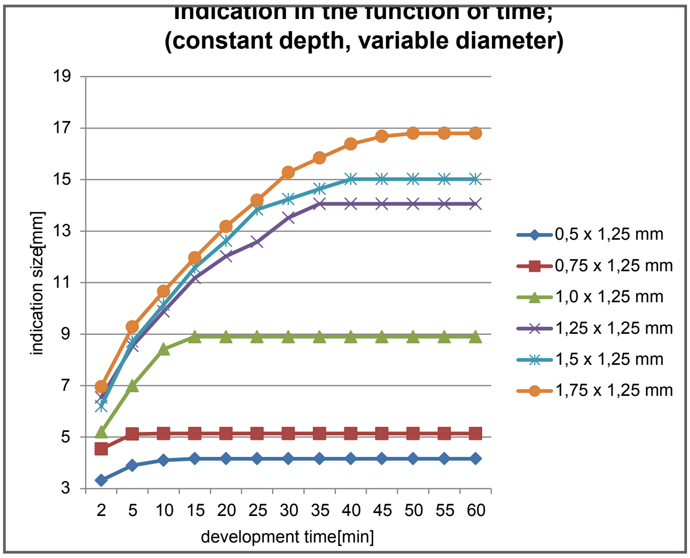

Fig. 8. Results of penetrant tests of the samples with the openings of a nominal depth of h = 1.25 mm and various diameters

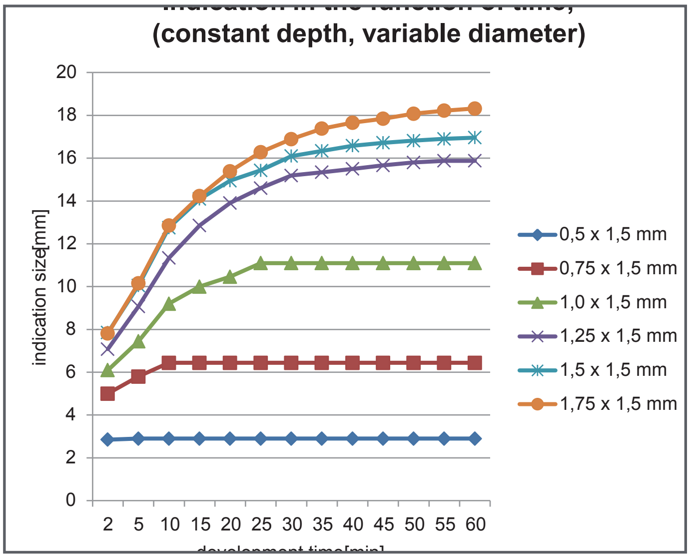

Fig. 9. Results of penetrant tests of the samples with the openings of a nominal depth of h = 1.5 mm and various diameters

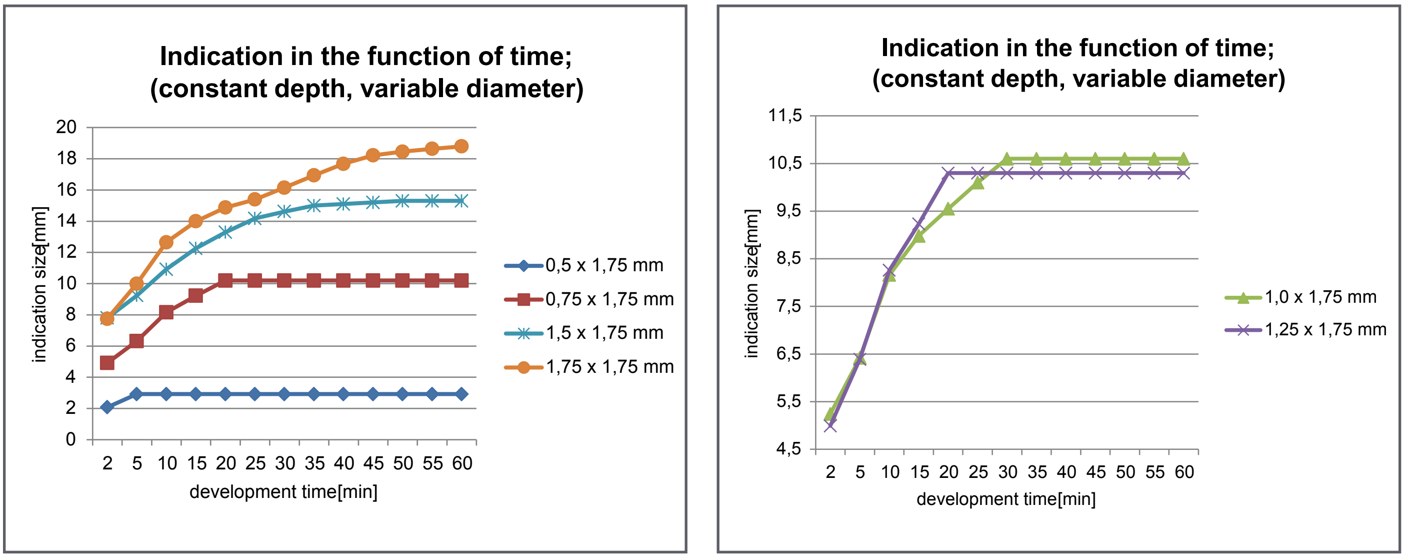

Fig. 10. Results of penetrant tests of the samples with the openings of a nominal depth of h = 1.75 mm and various diameters. Note: in Figure 10 the correlations dependent overlap. For this reason, broken lines representing indications from the openings ø 1.0 x 1.75 mm and ø 1.25 x 1.75 mm, are presented in a separate diagram

depth – imperfection-related terminology consistent with PN-EN ISO 6520-1) were connected with segments, thus determining a broken line demonstrating the course of correlation, the obtainment of which constituted the subject of the work undertaken.

The analysis of the courses of broken lines reveals that an increase in the diameter is usually accompanied by an increase in the maximum size of the indication obtained from the corresponding imperfection. Such a result is consistent with expectations. However, such an observation is not quite represented by the results demonstrated in Figures 5, 6 and 10. In the first case (Fig. 5) the maximum dimension indications from the opening ø 0.75 × 0.5 mm are greater than those from the openings ø 1.0 × 0.5 mm and ø 1.25 × 0.5 mm. Similarly, the indications from the opening ø 1.0 × 0.5 mm are greater than those from the opening ø 1.25 × 0.5 mm. However, it should be noted that the difference between the indications from the openings ø 0.75 × 0.5 mm, ø 1.0 × 0.5 mm and ø 1.25 × 0.5 mm is insignificant. The boundary values of the indications (Table 2, ø 0.75 through ø 1.25 for h = 0.5 mm) from these openings are restricted within a range from 6.10 mm (ø 1,25) to 7.46 mm (for ø 0.75). As can be seen, the difference between the indications amounts to a mere 1.36 mm and as such can be deemed negligible, even more so that the indications from the opening ø 1.0 adopt intermediate values. A similar situation can be observed in Figure 10. The boundary values of the indications from the openings ø 0.75 × 1.75 mm, ø 1.0 × 1.75 mm and ø 1.25 × 1.75 mm (Table 2, h = 1.75 mm) can be rated as belonging to the same set. For this reason, the broken lines determined overlap. A slightly different effect can be observed in Figure 6. The boundary values of the indications from the opening ø 1.5 × 0.75 are greater than those from the opening ø 1.75 × 0.75 mm (Table 2, h = 0.75 mm). The indications from the opening ø 1.0 × 0.75 mm are also characterised by greater values than those from the opening ø 1.25 × 0.75 mm. The differences between the indications amount to 1.74 mm and 1.38 mm respectively and, as in the previous cases, can be regarded as negligible.

The presented imperfections of the courses of some broken lines are at variance with expectations. However, it is necessary to take into consideration the fact that the process of penetrant testing includes a number of necessary stages, each of which, due to test sensitivity, must be performed with particular attention to detail as each negligence, usually unintended, decreases the sensitivity of a given test, decreasing its final result. The quality of openings simulating the pores (e.g. roughness of the drill surface, roughness of the surface around the opening inlet, local deformations of the inlet itself etc.) also affects the course of penetrant testing. In view of the foregoing, it is easy to account for the inaccuracy of the course of some broken lines revealed in the figures.

The analysis of the course of individual broken lines is also of some interest. In almost all of the cases analysed, at the initial stage of indication formation (development time from 0 to 5 minutes) the broken lines are characterised by a significant inclination in relation to the X-axis, i.e. to the development time axis, which indicates the significant dynamics of these indications increases. An exception is the line representing the opening ø 0.5×1.5 mm. The dynamics of the indication increase is almost invisible in this case. Clearly visible, yet lower than that of other lines, are the dynamics depicted by the lines representing the openings ø 0.5×1.25 mm and ø 0.75×1.25 mm. As can be seen, the low dynamics of penetrant indication increase is characteristic of the openings simulating the pores of a small diameter and relatively significant depth.

In the development time range from approximately 10 minutes to approximately 20 minutes, in most of the cases considered, the dynamics of indication increase decreases or indications become stable. Only the indications from the greatest simulated pores (ø = 1.25-1.75 mm and h = 1.0-1.75 mm) require a minimum of 30-40 minutes to become stable or tend to increase slightly. However, these pores of a relatively large diameter are rather seldom in welding practice and thus information concerning their course should not play a decisive role in terms of joint diagnostics as such pores are usually repaired without analysing the possibility of their operational acceptance. Nevertheless, the tests performed revealed that during the penetrant inspection of welded joints made of high-alloy steels, extension of the normative indication development time to approximately 45 minutes is justified.

On the basis of the determined correlation between the sizes of indications and their development time, in the function of pore sizes, it has become possible to estimate the depth of pores. An example of such estimation is presented and described in Figure 11.

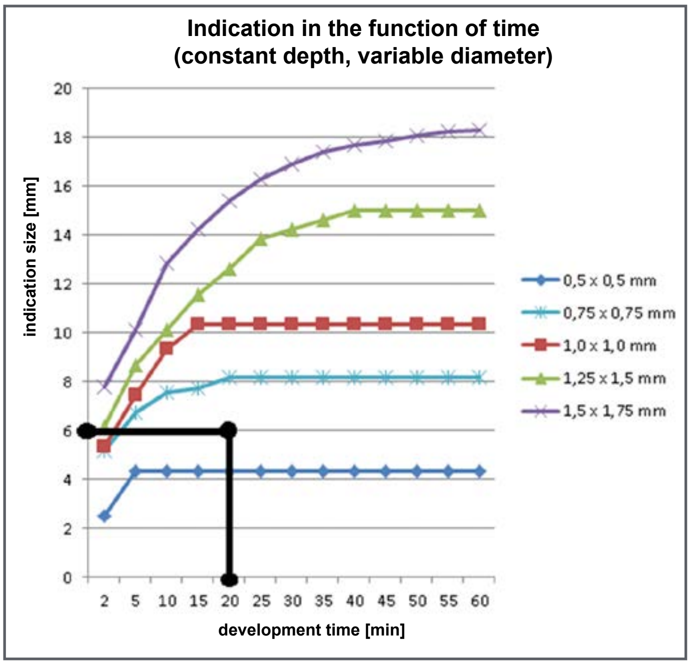

Fig. 11. Example of determination of estimated depth of pores in welded joints made of high-alloy steels. Measured values: the size of an indication – 6 mm, development time: 20 minutes, pore diameter – 0.6 mm. As can be seen, the point of the intersection of the coordinates 6 mm and 20 minutes lies between the lines representing a pore depth of 0.5 mm and 0.75 mm. It is therefore possible to conclude that the depth of the pore of the diameter of 0.6 mm amounts to approximately 0.6 mm.

Summary and Conclusions

The conducted penetrant tests of the specimens with openings simulating surface pores revealed that the undertaken target of the research work had been reached. The determined dependences make it possible to estimate the depth of pores in welded products made of high-alloy steels. Such information should facilitate the decision whether to accept a given product for operation or to repair it. It should also be mentioned that in some cases of determined broken lines, stabilisation occurs after the passage of a development time amounting to as much as 30-40 minutes. This fact suggests that during penetrant tests of welded joints made of high-alloy steels the aforesaid time should be extended in relation to the normative time amounting to 10-30 minutes. In this case the adoption of a 45-minute development time seems reasonable as regards the detection of all unacceptable surface imperfections. The broken lines determined are only an approximation of real courses, yet they are sufficient for estimate calculations which can be used in welding practice.

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 the possibility of estimating depths of surface porosity present in welded products made of high-alloy steels;
– analysis of penetrant test results indicates that the maximum development time of indications on surfaces of high-alloy steels should be extended to a minimum of 45 minutes.

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Reference standards:

– PN-EN ISO 3452-1: Non-destructive testing — Penetrant testing — Part 1: General principles
– PN-EN ISO 3452-2: Non-destructive testing — Penetrant testing — Part 2: Testing of penetrant materials
– PN-EN ISO 3452-3: Non-destructive testing — Penetrant testing — Part 3: Reference test blocks
– PN-EN ISO 3452-4: Non-destructive testing — Penetrant testing — Part 4: Equipment
– PN-ISO 3058: Non-destructive testing — Aids to visual inspection — Selection of low-power magnifiers
– PN-EN ISO 3059: Non-destructive testing — Penetrant testing and magnetic particle testing - Viewing conditions
– PN-EN ISO 12706: Non-destructive testing — Penetrant testing — Vocabulary
– PN-EN ISO 6520-1: Welding and allied processes — Classification of geometric imperfections in metallic materials — Part 1: Fusion welding