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Dye-penetrant method assessment of the size of pores in welded joints made of aluminium and its alloys

Abstract: The work included the penetrant inspection carried out on AlMg5 aluminium alloy 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 dependences determined enable estimating the depth of pores in welded products made of aluminium and its alloys. The information obtained should enable the decision-making concerning the acceptance of a product for operation or the necessity of repairing it. The tests also included the determination of optimum indication development time for aluminium and its alloys.

Keywords: NDT, penetration tests, aluminium, discontinuities, pores

Introduction

In most cases, welded joints are characterised by deviations, i.e. welding imperfections, from the ideal condition. As such imperfections reduce operational properties of joints, their type, number, and size should be the lowest as possible and ensure safe and failure-free operation of a welded product during its entire active life. In order to achieve this goal many various non-destructive tests are used. Among these is the liquid-penetrant inspection method, rated as one of the oldest, and most commonly applied in industry.

Liquid-penetrant inspection makes it possible to discover solely surface discontinuities including, among others, porosity. The depth of pores can be significant and which, as regards the leaktightness and active life of a joint, is highly undesirable. The possibility of estimating the size of pores is of great practical importance as it may facilitate decision-making concerning the acceptance of a tested product for operation or the necessity of repairing it.

The liquid-penetrant method enables the visualisation of discontinuities in the form of a red (most common) or shining indication (Fig. 1) [1].

a)

b)

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

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The depth of pores can be estimated only on the basis of this indication. Research has been undertaken to define the dependence between the size of an indication and the time of its development and the size of pores [2].

Such information can be useful in the technical diagnostics of a product tested by means of the dye-penetrant method.

The tests described below are the continuation of the research work presented in the publication [3]. The tests involved the use of EN AW-5019 (AlMg5) aluminium alloy, i.e. one of the most popular corrosion resistant parent metals used in welded structures.

Test pieces

In order to determine dependences which enable the assessment of the depth of pores detected by means of dye-penetrant inspection it was necessary to use the simulation of such discontinuities in the form of non-passthrough openings made in aluminium alloy plates. In order to optimise the liquid-penetrant inspection as well as for the sake of the accuracy of indications, 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.

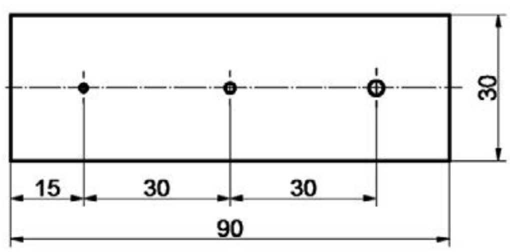

Fig. 2. Shape and dimensions of AlMg5 aluminium alloy plates with openings tested using the dye-penetrant method. Thickness of material: 4 mm

Table 1. Designation and nominal dimensions of openings in aluminium alloy plates tested using the liquid-penetrant method.

No.	Plate designation	Opening designation	Nominal dimensions of openings	
			diameter [mm]	depth [mm][1)]
1		1	0.50	
2	I	2	0.75	
3		3	1.00	0.50
4		1	1.25	
5	II	2	1.50	
6		3	1.75	
7		1	0.50	
8	III	2	0.75	
9		3	1.00	0.75
10		1	1.25	
11	IV	2	1.50	
12		3	1.75	
13		1	0.50	
14	V	2	0.75	
15		3	1.00	1.00
16		1	1.25	
17	VI	2	1.50	
18		3	1.75	
19		1	0.50	
20	VII	2	0.75	
21		3	1.00	1.25
22		1	1.25	
23	VIII	2	1.50	
24		3	1.75	
25		1	0.50	
26	IX	2	0.75	
27		3	1.00	1.50
28		1	1.25	
29	X	2	1.50	
30		3	1.75	
31		1	0.50	
32	XI	2	0.75	
33		3	1.00	1.75
34		1	1.25	
35	XII	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 liquid-penetrant inspection of the plates with simulated pores involved the use of the set of testing aerosols designated, following the requirements of standard PN-EN ISO 3452-1, as IICe-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 liquid-penetrant inspection of plates with simulated pores

The aerosols used in the tests were as follows:
- penetrant – red colour, type BDR-L, lot no.: 20 15, filling date: 09/2012,
- 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 and materials:
- 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 liquid-penetrant inspections of the plates were conducted in the following conditions:
- temperature of tested surface – 22°C,
- ambient humidity – 23%,
- penetration time – 15 minutes,
- development time – 30 minutes,
- illuminance of tested surface – 584 lx,
- observation distance –10-30 cm,
- observation angle – from 60 to 90°.

Conducted inspections 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 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 ISO 3452-1, according to which it should be contained within a 10-30 minute range. The samples with developed indications are presented in Figure 4. The test results, in the form of the measurements of the greatest indication values, are presented in Table 2.

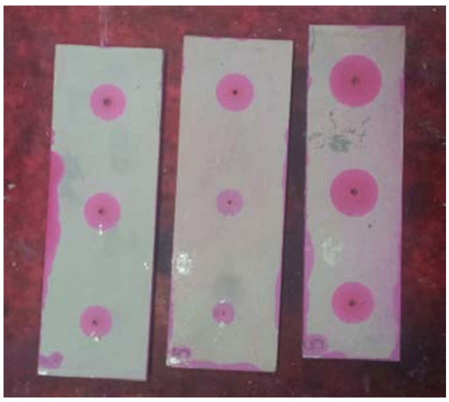

Fig. 4. Samples with developed indications of simulated pores.

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

No.	Nominal opening diameter [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)]						
1	2	3.42	4.18	4.90	5.22	5.84	5.98
2	5	3.48	4.38	5.14	6.28	6.42	6.96
3	10	3.56	4.4	5.32	6.66	6.72	7.36
4	15	3.56	4.46	5.32	6.66	6.74	7.4
5	20	3.56	4.46	5.32	6.66	6.74	7.4
6	25	3.56	4.46	5.32	6.66	6.74	7.4
7	30	3.56	4.46	5.32	6.66	6.74	7.4
	h = 0.75 mm[1)]						
8	2	3.62	3.92	5.54	4.42	5.15	5.68
9	5	4.26	4.98	6.62	6.38	6.72	7.18
10	10	5.26	5.54	7.72	8.02	8.74	9.08
11	15	5.34	5.56	8.55	8.16	9.58	9.64
12	20	5.34	5.56	8.55	8.34	10.08	10.02
13	25	5.34	5.56	8.55	8.36	10.08	10.02
14	30	5.34	5.56	8.55	8.36	10.08	10.02
	h = 1.00 mm[1)]						
15	2	3.6	4.92	5.56	4.26	5.42	6.08
16	5	4.48	6.04	6.85	6.16	6.94	7.8
17	10	5.64	6.92	8.44	8.22	9.06	10.1
18	15	5.86	7.18	9.72	9.68	10.82	11.74
19	20	5.92	7.22	10.22	10.56	12.04	13.14
20	25	5.92	7.22	10.22	10.9	12.82	13.66
21	30	5.92	7.22	10.22	10.9	13.02	14.08
	h = 1.25 mm[1)]						
22	2	3.56	3.98	5.52	6.54	6.2	6.96
23	5	5.22	5.36	7.32	8.54	8.7	9.28
24	10	5.28	5.88	7.84	9.88	10.14	10.66
25	15	5.3	6.02	8.14	11.18	11.58	11.96
26	20	5.58	6.2	8.22	12.02	12.62	13.18
27	25	5.58	6.2	8.22	12.58	13.84	14.2
28	30	5.58	6.2	8.22	13.52	14.24	15.28
	h = 1.50 mm[1)]						
29	2	2.12	4.02	4.22	5.92	7.06	7.44
30	5	2.2	5.94	6.3	8.32	9.38	9.54
31	10	2.2	7.18	7.68	9.56	10.68	10.82
32	15	2.2	8.18	8.52	11	11.98	12.14
33	20	2.2	9.2	9.24	12.2	12.92	13.34
34	25	2.2	9.68	9.7	12.72	13.94	14.12
35	30	2.2	9.68	9.7	13.06	14.38	14.94

[1)] h – nominal opening depth.

Table 2 - continuation

No.	Nominal opening diameter [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)]						
36	2	3.38	3.92	4.12	6.32	7.8	8.26
37	5	4.12	5.1	5.32	7.68	9.24	9.78
38	10	4.46	5.72	6.2	8.38	10.92	11.12
39	15	4.46	6.2	7.16	9.56	11.76	12.4
40	20	4.46	6.2	7.62	10.04	12.2	13.74
41	25	4.46	6.2	7.84	10.72	12.48	14.5
42	30	4.46	6.2	7.84	10.8	12.48	15.22

[1)] h – nominal opening depth.

Analysis of inspection results

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

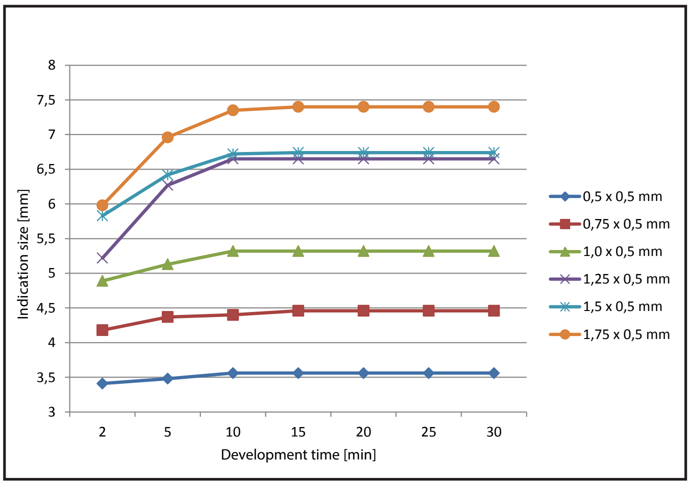

Fig. 5. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 0.50 mm and various diameters.

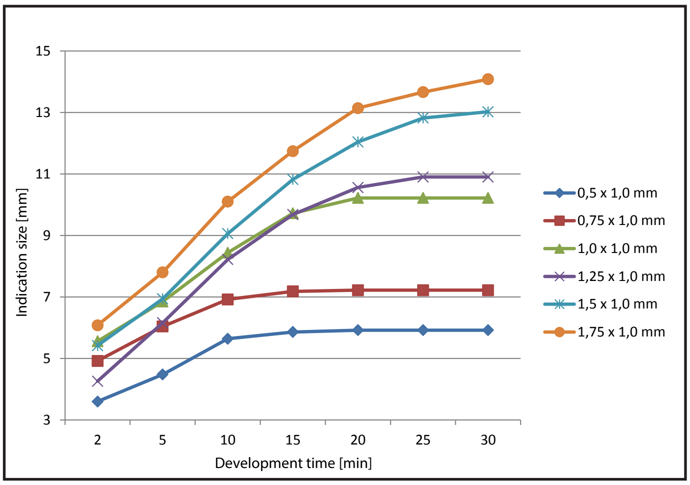

Fig. 7. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 1.00 mm and various diameters

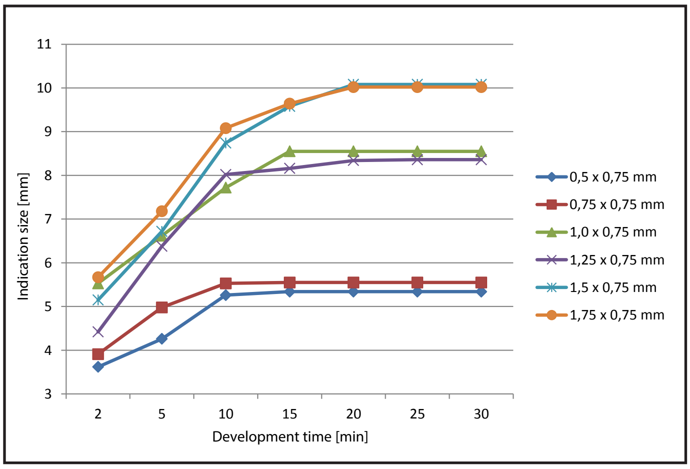

Fig. 6. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 0.75 mm and various diameters.

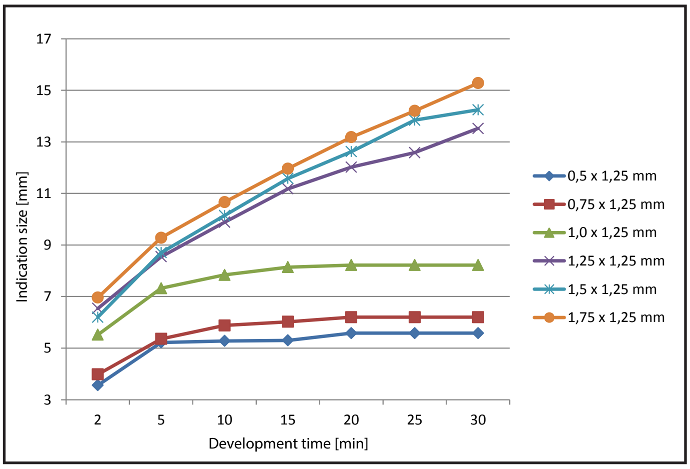

Fig. 8. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 1.25 mm and various diameters.

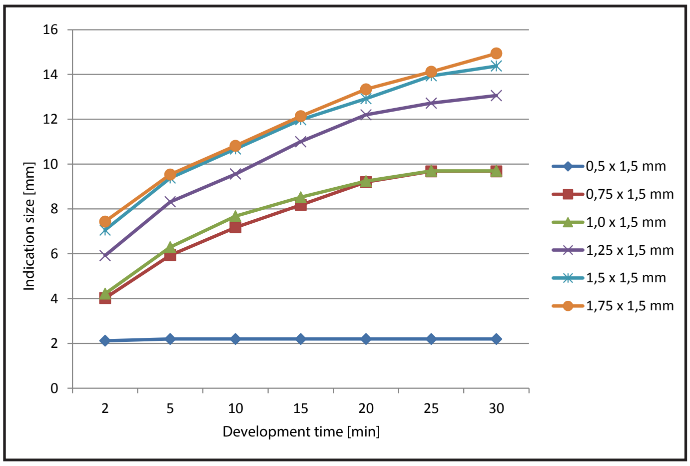

Fig. 9. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 1.50 mm and various diameters.

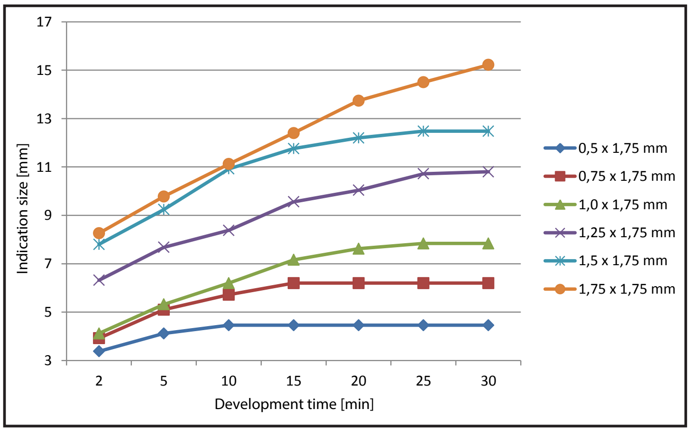

Fig. 10. Results of liquid-penetrant inspections of the samples with the openings of a nominal depth of h = 1.75 mm and various diameters

As can be seen in Figures 5-10, the coordinates of individual measurement points are determined by the measured size of indication and its time of development. Points of various coordinates but related to the same size of a surface pore (pore of the same diameter and depth – imperfection terminology according to PN-EN ISO 6520-1) 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 is, in each case, accompanied by an increase in the maximum size of the indication obtained from this imperfection. 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 the cases. An exception can be observed in the case of the lines representing the pores of the smallest depth (h=0.5 mm) and smallest diameters (ø=0.5 mm, ø=0.75 mm and ø=1.0 mm)(Fig. 5), where the dynamics of indication increase is low. The low dynamics of indication increase is also revealed by the line representing the pores having a small diameter (ø=0,5 mm) and relatively significant depth (h=1.5 mm)(Fig. 9). In the development time range between 5 minutes and 10 minutes the dynamics of indication increase usually decreases. However, in most cases the lines analysed are characterised by the significant stabilisation of indications after the development time of approximately 15-20 minutes. Only the indications of the greatest simulated pores (ø=1.25-1.75 mm and h=1.0-1.75 mm)(Fig. 7-10) tend to be stable after the passage of the normative development time, i.e. after approximately 30 minutes, or even show an increasing tendency. However, such big pores are rarely encountered in welding practice and the information about their course does not play any decisive role in terms of joint diagnostics. Such pores are usually repaired without analysing their possible admission to operation. The above deliberations justify the conclusion that for aluminium and its alloys the indication development time (of pores and, presumably, other surface imperfections) during dye-penetrant inspection can be reduced to approximately 15-20 minutes. In the case of a great number of tests this can bring significant economic effects due to work time savings.

In Figures 6-8 it is also possible to observe the interlacing of some broken lines. For instance, in the area of development time from 2 minutes to 15 minutes it is possible to observe the intersection of the lines determining the pores of dimensions: ø1.0×0.75 mm and ø1.25×0.75 mm, ø1.0×0.75 mm and ø1.5×0.75 mm (Fig. 6), ø0.75×1.0 mm and ø1.25×1.0 mm, ø1.0×1.0 mm and ø1.25×1.0 mm (Fig. 7) and ø1.25×1.25 mm and ø1.5×1.25 mm (Fig. 8).

In the first case (Fig. 6), the line representing the pores of the smaller diameter (ø1.0) also shows the maximum indications greater than the line representing the pores of the greater diameter (ø1.25). This observation is inconsistent with expectations. However, it is necessary to take into consideration the fact that the penetrant inspection process is composed of a number of phases to be carried out. Due to the test sensitivity, each of the phases must be conducted with great attention to detail as each, usually unintended, negligence in the course of the process decreases the test sensitivity affecting the final result. In view of the foregoing, it is easy to account for the inaccuracy of the course of some broken lines revealed in the figures.

On the basis of the determined dependence between the size of an indication and its development time, in the function of the size of an imperfection, it has become possible to estimate the depth of pores. A general procedure in this scope includes the following:

- measurement of a pore diameter by means of a caliper or universal weld gauge of accuracy of at least 0.1 mm;
- performance of liquid-penetrant inspection following the requirements of standard PN-EN ISO3452-1;
- providing tested surface 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.

An example of how to determine the estimated depth of pores is presented in Figure 11.

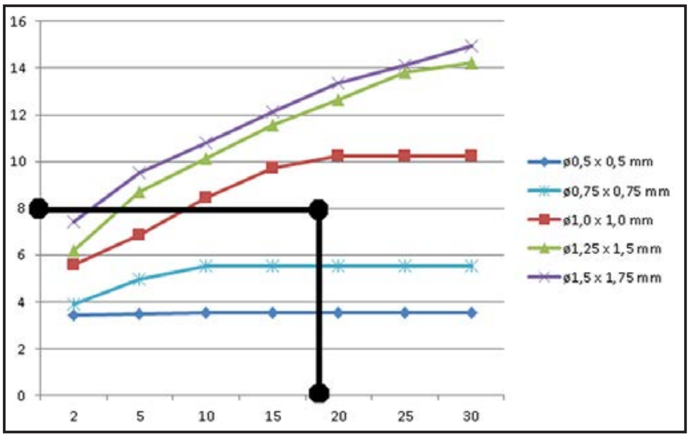

Fig. 11. Example of determination of estimated depth of pores in welded joints made of aluminium and its alloys. Measured values: the size of an indication – 8 mm, development time: 17 minutes, pore diameter – 0.8 mm. As can be seen, the point of the intersection of the coordinates 8 mm and 17 minutes lies slightly below the broken line representing the pore of the dimensions ø1.0 x 1.0 mm. It is therefore possible to conclude that the depth of the pore of the diameter of 0.8 mm amounts to approximately 1.0 mm.

Summary and conclusions

The conducted liquid-penetrant inspections of the samples with openings simulating surface pores revealed that the undertaken target of the research had been reached. The determined dependences make it possible to estimate the depth of pores in welded products made of aluminium and its alloys. 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 most cases of determined broken lines they undergo stabilisation after the passage of development time amounting to approximately 15-20 minutes. This fact suggests that during penetrant inspections of joints made of aluminium and its alloys the aforesaid time can be regarded as sufficient for detecting unacceptable internal imperfections. The broken lines are only an approximation of real courses, yet they are sufficient for estimate calculations which can be used in welding practice. The research work described above is expected to be continued using other parent metals used in the production of welded structures.

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 porosity present in welded products made of aluminium and its alloys;
- analysis of dye penetrant inspection results indicates that the maximum development time of indications on surfaces of aluminium and its alloys can be limited to approximately 15 – 20 minutes;
- research work should be continued with other parent metals used in the production of welded structures.

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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