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Dye Penetrant Tests of Welded Joints Made in Structural Steel

Abstract: The article presents imperfections tested using penetrant methods. The research described in the article was concerned with imperfections regarded as the most hazardous, i.e. cracks. The tests involved the formation of natural cracks in structural steel S355J2C+N. The cracks were measured in terms of their width and the roughness profile of their surface. The research involved a number of penetrant tests aimed to determine how a given factor (crack width or crack surface roughness) affected the time of development in penetrant tests of joints made in structural steel.

Keywords: non-destructive tests of joints, dye penetrant tests, structural steel S355J2C+N, welding imperfections

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Introduction

The testing of weld properties has become the key element of the quality control in welding engineering. Because of the fact that welding is a special process, welding imperfections (if any) may only be disclosed once the welding process is complete. Welding imperfections and defects formed during welding significantly affect the strength of welds. The most hazardous imperfections present in welded joints are cracks which, if open on the surface of materials being subjected to examination, can be detected using penetrant tests. Cracks of welded joints result from stresses triggering the local exceeding of the tensile strength of a given material. Cracks constitute significant concentrators of stresses, yet small sizes of cracks may preclude their detection. Fortunately, cracks can be successfully detected using, e.g. dye or fluorescent, penetrant tests (Fig. 1) enabling the detection of cracks being a mere 0.5 µm in width. In penetrant tests, the time of development, i.e. the

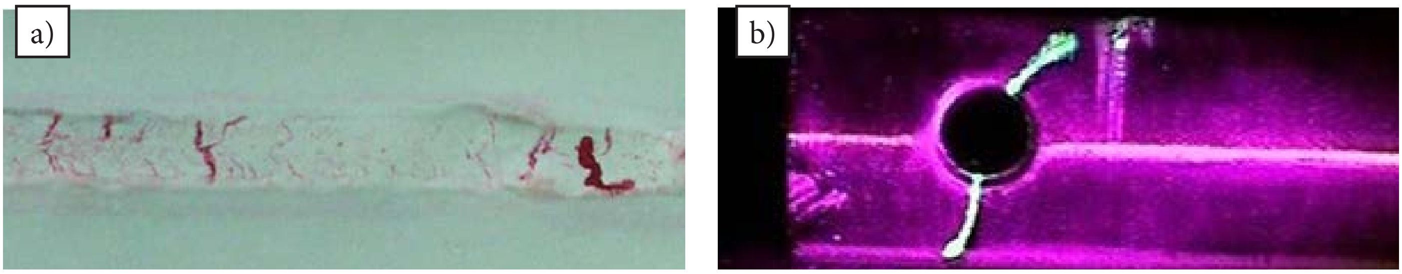

Fig. 1. Indications obtained during penetrant tests performed using a) dye penetrant method (surface observed in the natural light) and b) fluorescent penetrant method (surface observed using UV-A radiation)

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time after which penetrant reaches the surface, varies between several minutes and as many as 24 hours. This research aims to ascertain how the crack width and crack surface roughness affect the time of development in welded joints made of structural steels and what development times should be recommended in relation to the above-named materials. To obtain more accurate results, the tests were performed using natural cracks [1-3].

Test Specimens

The tests involved the use of (test) structural steel S355J2C+N. The determination of crack widths involved making 4 butt joints (150x300x6 mm) (Fig. 2). The butt joints were welded using the TIG method without a filler metal.

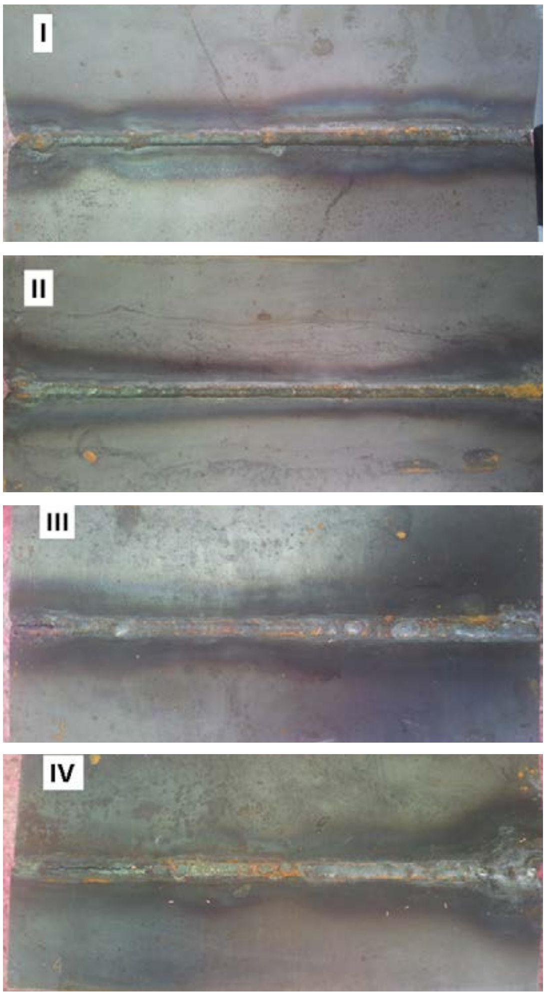


Fig. 2. Butt joints made of the structural steel. Roman numerals represent numbers of successive joints

Tests on Natural Cracks

Before the tests and measurements, the specimens were thoroughly cleaned, i.e. post-processing remains were removed and the surface to be tested was degreased in an ultrasonic washer using extraction naphtha and cleaning

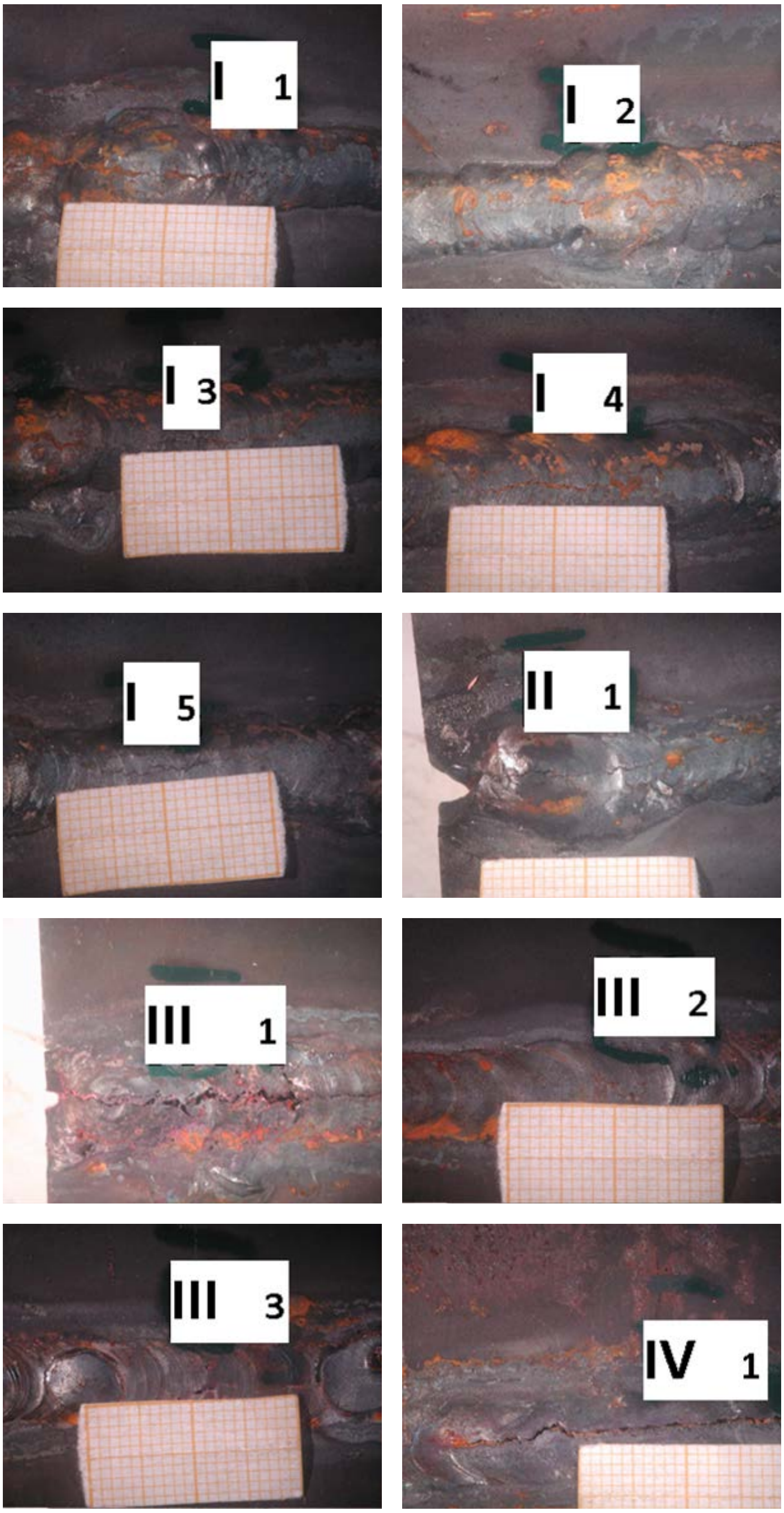
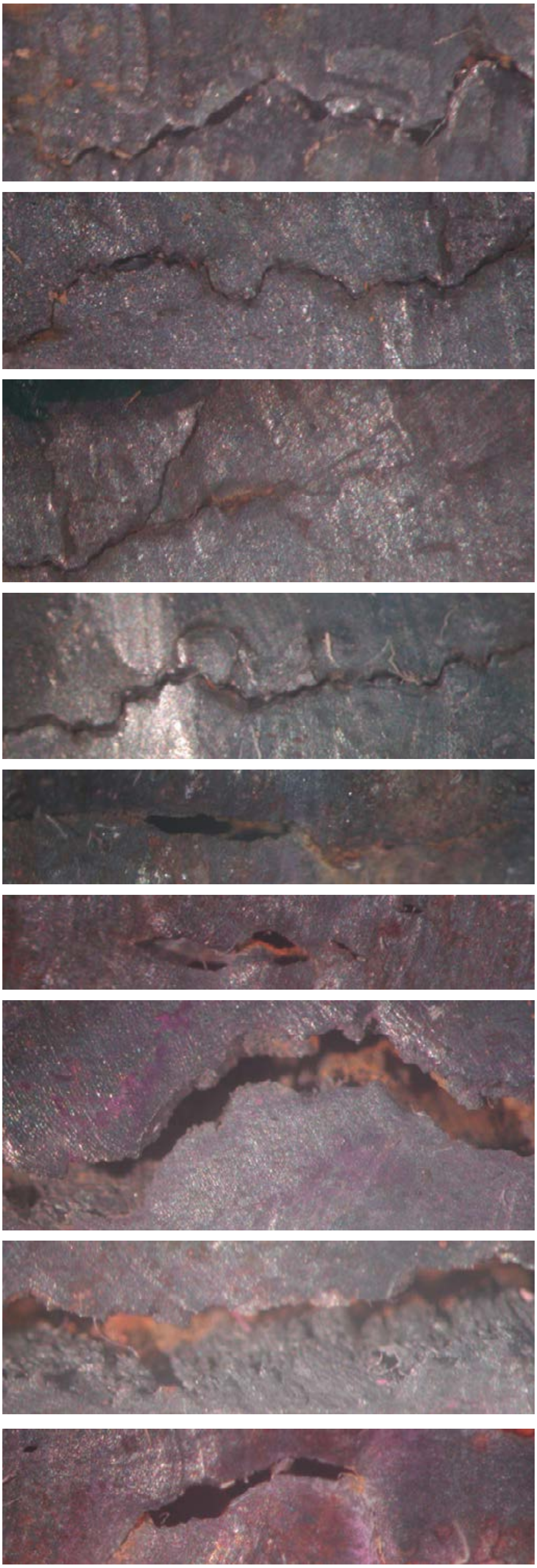


Fig. 3. Exemplary cracks in the butt joints made of the structural steel (magnified 4x). Roman numerals represent numbers of successive joints; Arabic numerals represent number of successive cracks in a given joint

Fig. 4. Olympus SZX9 stereoscopic microscope

solvent. After washing, the specimens were dried at a temperature of approximately 20°C, using a stream of compressed air. As expected, the butt joints developed cracks (see Fig. 3).

Macroscopic photographs of the cracks were made using an Olympus SZX9 stereoscopic microscope (Fig.4) at 4x and 28.5x magnification (Fig. 3 and 5). The widths of the cracks were measured using the Auto CAD 2012 software programme and digital photographs containing visible cracks. The measurement accuracy amounted to 4 μm. The number of measurements performed for each crack varied as measurements of crack widths were performed at 1 millimetre intervals. Therefore, depending on the length of each crack, the number of measurements varied between a few to more than a hundred. The designations and widths of the cracks in the butt joints are presented in Table 1.



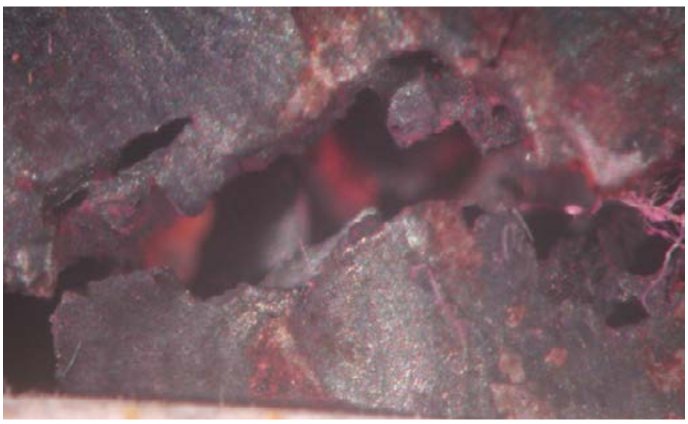


Fig. 5. Exemplary cracks in the butt joints made of the structural steel (magnified 28.5x)

Table 1. Designations and the width of the cracks in the butt joints made of the structural steel

Number of joint	Crack number	Crack width, μm
I	1	4÷344
I	2	4÷112
I	3	8÷108
I	4	20÷284
I	5	16÷104
II	1	12÷92
III	1	16÷1120
III	2	12÷276
III	3	8÷412
IV	1	4÷1144

The width of 10 measured cracks was restricted within the range of 4 μm to 1144 μm. Before breaking, the crack areas (in order to measure the roughness profile of the crack surfaces) were subjected to dye penetrant tests. The penetrant tests of the cracks involved the use of a set of testing aerosols designated, following the requirements of PN-EN ISO 3452-1, as IICe-2, the "Diffu-Therm" type, manufactured by H. Klumpf Techn. Chemie KG D-45699 Herten. The aerosols used in the tests were as follows:

- penetrant – red colour, type BDR-L, lot no.: 20 15, filling date: 09/2015,
- remover – type BRE, lot no.: 22 16, filling date: 02/2015,
- developer – type BEA, lot no.: 23 16, filling date: 06/2015,
- 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 a measurement accuracy of 0.02 mm,
- workshop magnifying glass (4x),
- non-shredding fabric.

The penetrant tests of the cracks were conducted in the following conditions:

- temperature of tested surface: 22°C,
- ambient humidity: 23%,
- penetration time: 10, 30 and 60 minutes,
- development time: until the end of indication development,
- illuminance of tested surface: 584 lx,
- observation distance: 10-30 cm,
- observation angle: from 60 to 90°.

The tests involved all of the cracks (in several tests) with variables being the time of penetration and that of development. The tests were performed in relation to penetration times of 10, 30 and 60 minutes, where the penetrant was applied several times so that the surface subjected to the test would be permanently covered by the penetrant. The varied penetration times made it possible to test the effect of penetration time on development time. An additional measurement involved a development time of 60 minutes accompanying the single application of the penetrant. Measurements of indications were performed after 5, 10, 15, 20, 30, 40, 50, 60 minutes etc., until the stoppage of the development of indications (Table 2). In relation to each specimen only one indication, i.e. of the longest crack, was recorded. Each penetrant test performed using specific parameters was conducted 3 times and followed by the calculation of the arithmetic mean.

The measurements performed at the initial stage of indication appearance aimed at the more accurate determination of the dependence being the subject of this work and the dynamics of crack formation. The adopted maximum time of indication development exceeded the recommendations formulated in standard PN-EN ISO 3452-1, stating that the time of development should be restricted within the range of 10 minutes to 30 minutes. The time adopted in the tests was extended in order to determine the recommended time of indication development regardless of the recommendation specified in the above-named standard. The specimens with developed indications are presented in Figure 6.

Table 2. Sizes of indications originated in the cracks formed on the joints made of the structural steel. The penetrant was applied so that the entire tested surface was permanently covered by the penetrant. * – test joint covered by the penetrant once

Specimen number I

Time of penetration, min	Time of development, min																			
	5	10	15	20	25	30	40	50	60	70	80	90	100	110	120	140	170	200	230	260
10	37.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
30	38.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	39.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60*	43.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Specimen number II

Time of penetration, min	Time of development, min																			
	5	10	15	20	25	30	40	50	60	70	80	90	100	110	120	140	170	200	230	260
10	21.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
30	21.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	21.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60*	22.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Specimen number III

Time of penetration, min	Time of development, min																			
	5	10	15	20	25	30	40	50	60	70	80	90	100	110	120	140	170	200	230	260
10	41.0	42.0	43.0	44.0	44.5	45.5	46.0	-	-	-	-	-	-	-	-	-	-	-	-	-
30	40.0	41.0	42.0	43.0	43.5	44.0	44.5	-	-	-	-	-	-	-	-	-	-	-	-	-
60	40.0	41.0	42.0	42.5	43.0	43.5	44.5	-	-	-	-	-	-	-	-	-	-	-	-	-
60*	42.0	44.0	45.0	45.5	46.0	46.5	47.5	48.0	48.5	-	-	-	-	-	-	-	-	-	-	-

Specimen number IV

Time of penetration, min	Time of development, min																			
	5	10	15	20	25	30	40	50	60	70	80	90	100	110	120	140	170	200	230	260
10	84.0	87.0	89.0	90.0	91.5	92.5	93.5	94.5	-	-	-	-	-	-	-	-	-	-	-	-
30	84.0	86.5	88.5	90.0	91.0	92.0	93.5	94.5	-	-	-	-	-	-	-	-	-	-	-	-
60	83.0	86.0	88.0	89.0	90.5	92.0	94.0	95.0	-	-	-	-	-	-	-	-	-	-	-	-
60*	82.0	85.5	88.0	89.5	90.0	91.0	92.5	93.0	93.5	-	-	-	-	-	-	-	-	-	-	-

Note: Indication sizes provide information about the greatest values of indication in millimetres

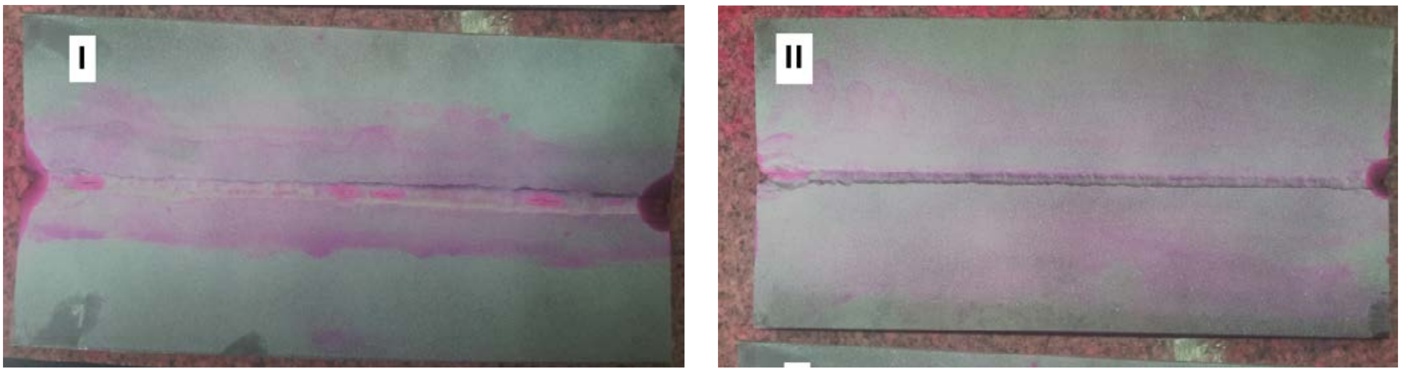


Fig. 6. Selected specimens made of the structural steel with indications originated in cracks. Roman numerals represent numbers of successive joints.

The penetrant tests of the structural steel specimens containing cracks revealed that one of the objectives of the research work discussed in this article was achieved. In cases of the joints made of structural steel, the identified differences of penetration times did not significantly affect the sizes of indications; the differences rather reflected the specific nature of the test process itself. The penetrant test process includes a number of phases, each of which should be performed paying great attention to detail. Each negligence in the process of testing, usually unintended, reduces the test sensitivity decreasing the final test result. In view of the foregoing it is easy to clarify a detected inaccuracy, i.e. a greater indication accompanying a shorter penetration time. In turn, a single application of penetrant did not significantly affect the results. In addition, it was observed that in most of the cases, the sizes of indications grew dynamically up to, approximately, the 5-10th minute of development time. At a later time, an increase in an indication was very slow and, in most of the cases, ended at, approximately, the 60th minute of development time (see the diagram in Fig. 7). This implies that when performing penetrant tests of joints made in structural steels, the above-named time could be regarded as sufficiently long in order to enable the detection of unallowed external imperfections, e.g. cracks. During the tests it was also noticed that the time of development extended along with an increase in the crack width. The penetrant tests were followed by measurements of crack surface roughness. In order to determine profiles of roughness in the cracks, the butt joints were fractured in the areas where the cracks were formed (Fig. 8).

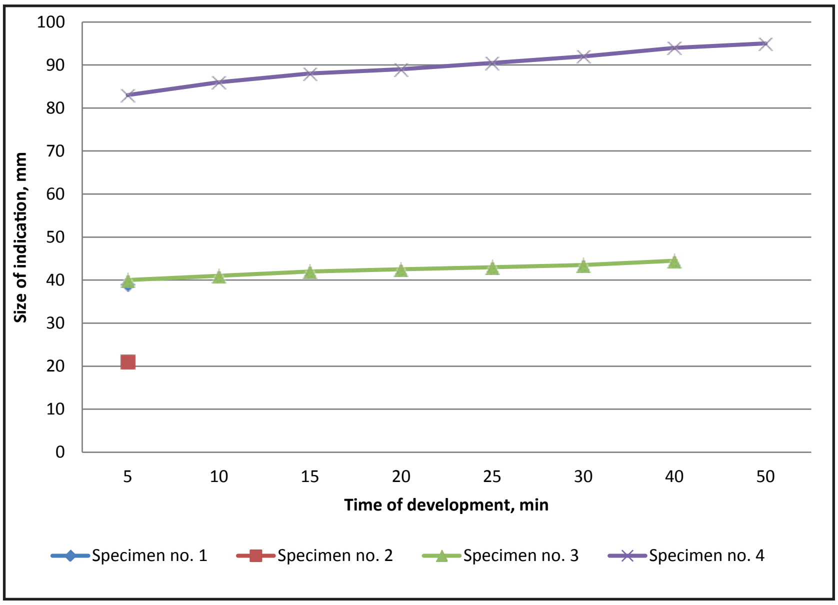


Fig. 7. Dependences between indication sizes and development times in relation to the cracks formed in the structural steel

Fig. 8. Butt joint made of the structural steel after the fracture in the crack area. Roman numerals represent numbers of successive joints; Arabic numerals represent numbers of successive cracks in a given joint

The rig used for testing the profile of roughness was provided with the Turbo Datawin-NT software programme integrated with a Hommel tester T1000 (contact profile measurement gauge) (Fig. 9). The measurement equipment enabled complex dimensional and statistical analyses of microgeometrical parameters as well as the visualisation of the stereometric structure of a surface subjected to measurement. The equipment made it possible to measure the following profiles:

– roughness (R),
– waviness (W),
– primary profile (P)

and roughness core parameters (Rk) as well as parameters of the motif-detection method (WD1 and WD2).

Fig. 9. Hommel tester T1000 contact profile measurement gauge

Fig. 11. Visualisation of the stereometric structure of the surface being measured

Such a wide range of measurements was necessary in order to determine correct values of the surface roughness profile. An issue posing difficulty was the waviness of the surface, the roughness of which was to be measured. As a result, the equipment made two measurements, i.e. of the surface profile and that of the roughness profile (Fig. 10).

After approximating the value obtained after measuring the surface profile, the software programme converts this value into the profile of roughness. In addition, during measurements, the screen displays the visualisation of the stereometric structure of the surface being measured (Fig. 11). The software programme integrated with the profile measurement gauge provides a lot of data concerning the surface being measured (Fig. 12). This work discusses one of these parameters, namely *Ra*, i.e. the average arithmetic deviation of the profile from the average line. The profile of roughness was measured for each crack in 3 areas; afterwards, measurement results were averaged (Table 3). The roughness of surface was measured in accordance with recommendations specified in standard PN-EN ISO 4288:2011E. The length of elementary segment l_r amounted to 0.8 mm or 2.5 mm, whereas the length of measurement segment l_t amounted to 4.8 mm and 15 mm respectively. The value of the elementary segment and the value of the measurement segment depend on the range of roughness expected on the surface being measured.

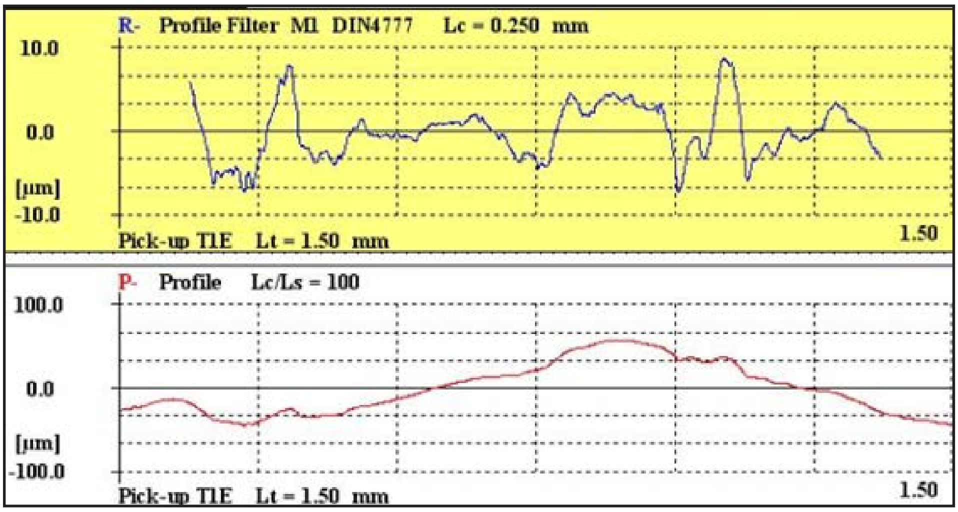


Fig. 10. Measurement of surface roughness (top) and of the profile (bottom)

Table 3. Roughness of surfaces of the cracks detected in structural steel S355J2C+N

Plate/joint	I	I	I	I	I	II	III	III	III	IV
Crack	1	2	3	4	5	1	1	2	3	1
Roughness *Ra*, µm	6.63	7.51	3.70	6.29	5.17	7.32	3.46	4.89	6.47	5.66

Note: Roman numerals represent numbers of successive joints; Arabic numerals represent number of successive cracks in a given joint

The roughness of crack surfaces was restricted within the range of 3.46 to 7.51. When comparing the results concerning the roughness of crack surfaces it was noticed that in relation to previously performed penetrant tests, the time of development was longer in cases of cracks characterised by greater surface roughness.

Concluding remarks

The analysis of the results obtained in the tests enabled the formulation of the following conclusions:

1. In cases of penetrant tests performed on structural steels, the time of penetration did not significantly affect the time of development and could amount to a mere 10 minutes.

2. In cases of tests involving structural steels, the single application of penetrant did not significantly affect the time of development and sizes of indications.

3. Each of the factors subjected to the tests significantly affected the time of development in penetrant tests, which was demonstrated by various times of development in relation to various cracks.

4. It was noticed that the increase in crack surface roughness was accompanied by a longer development time. This could be attributed to the fact that the greater surface development was connected with the greater volume of penetrant present in a discontinuity.

5. Because of the greater volume of penetrant present in the crack, the increase in the crack width also extended the time of development.

6. When performing penetrant tests of structural steels, it is recommended that the time of development be extended to approximately 60 minutes, In most cases, the above-named time should be sufficient to enable the detection of unallowed welding imperfections.

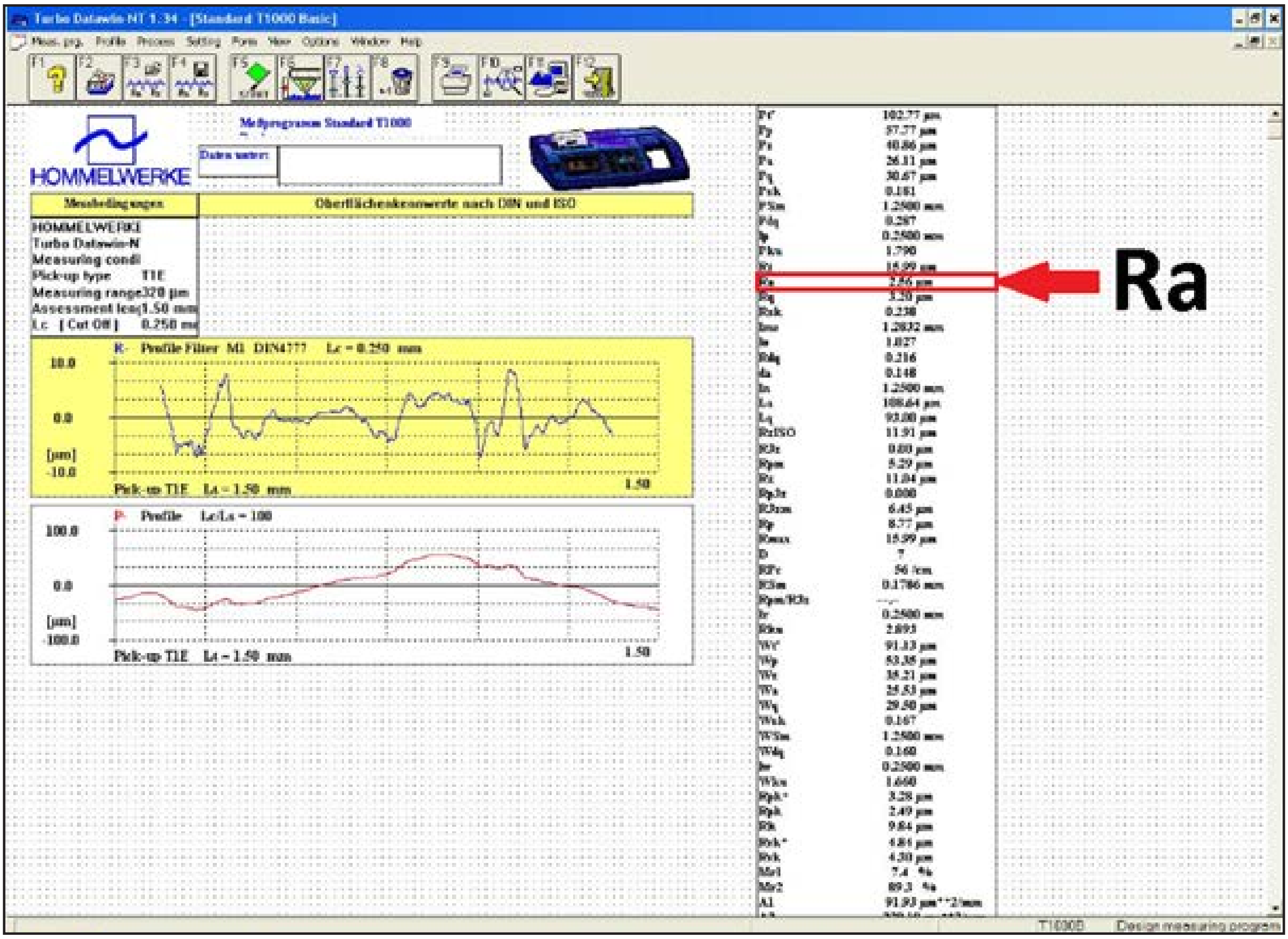


Fig. 12. Window of the Turbo Datawin-NT software programme. The red colour indicates parameter *Ra* (analysed in the work)

References:

[1] Czuchryj J., Hyc K.: *Dye-penetrant method assessment of the size of surface discontinuities in products made of carbon structural steel*. Biuletyn Instytutu Spawalnictwa, 2012, no. 02, pp. 37-45 http://bulletin.is.gliwice.pl/article/dye-penetrant-method-assessment-size-surface-discontinuities-products-made-carbon-structural

[2] Czuchryj J., Irek P.: *Dye penetrant method of the assessment of the pores size in welded joints made of aluminium and its alloys*. Biuletyn Instytutu Spawalnictwa, 2014, no. 4, pp. 14-21 http://bulletin.is.gliwice.pl/article/dye-penetrant-method-assessment-pores-size-welded-joints-made-aluminium-and-its-alloys

[3] Czuchryj J., Irek P.: *Dye-Penetrant Method Assessment of the Size of Pores in Welded Joints Made of High-Alloy Steel*. Biuletyn Instytutu Spawalnictwa, 2015, no. 1, pp. 21-28 http://bulletin.is.gliwice.pl/article/dye-penetrant-method-assessment-size-pores-welded-joints-made-high-alloy-steel http://bulletin.is.gliwice.pl/article/dye-penetrant-method-assessment-size-pores-welded-joints-made-high-alloy-steel

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*