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Dye Penetrant Testing of Welded Joints Made of Nickel and its Alloys

Abstract: The article presents tests involving natural cracks, including measurements of the width of cracks and the profile of their surface roughness. The investigation also involved tests performed in order to observe how a given factor affects development times in penetrant tests as well as to determine what time of development is recommended for nickel and its alloys in order to detect unacceptable welding imperfections (cracks). The article also discusses the effect of penetration times on the duration of development times and sizes of indications in penetrant tests.

Keywords: non-destructive testing, dye penetrant testing, nickel alloys

DOI: *10.17729/ebis.2016.4/7*

Introduction

Welding processes can be accompanied by the formation of welding imperfections compromising the strength of welded joints. The most important imperfections in terms of welded structures are cracks. Surface cracks can be detected using various non-destructive testing methods. One of the most popular NDT methods is penetrant testing. During penetrant tests, a penetrant, supported by a developer, "leaves" a discontinuity to reach the surface subjected to the test. As a result, a dye or fluorescent technique-based indication is obtained (Fig. 1). The time after which a penetrant reaches the surface,

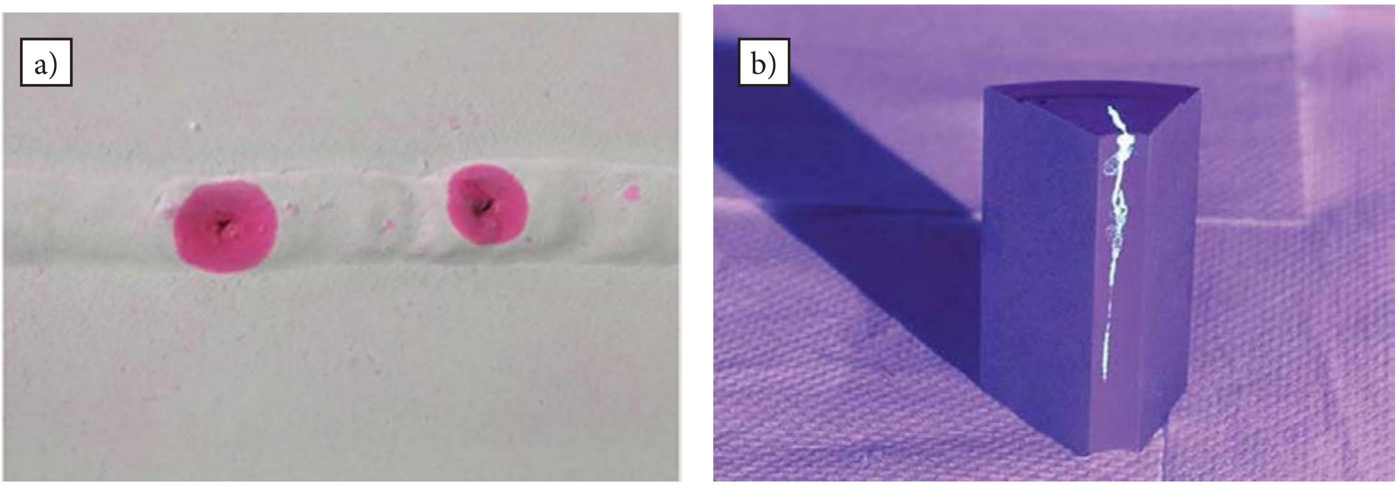

Fig. 1. Indications obtained during penetrant tests: a) using the dye penetrant method (observation of the surface in natural light), b) using the fluorescent method (observation of the surface in UV-A radiation)

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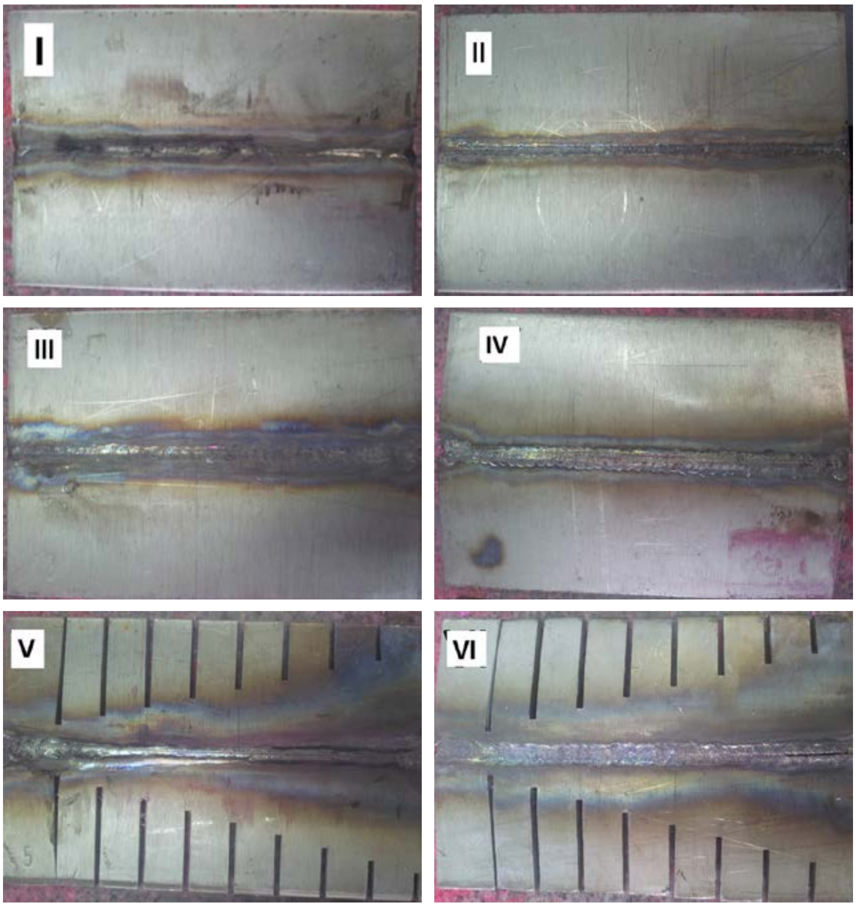

Fig. 2. Butt joints made of Nickel 200. Roman numerals represent numbers of successive joints

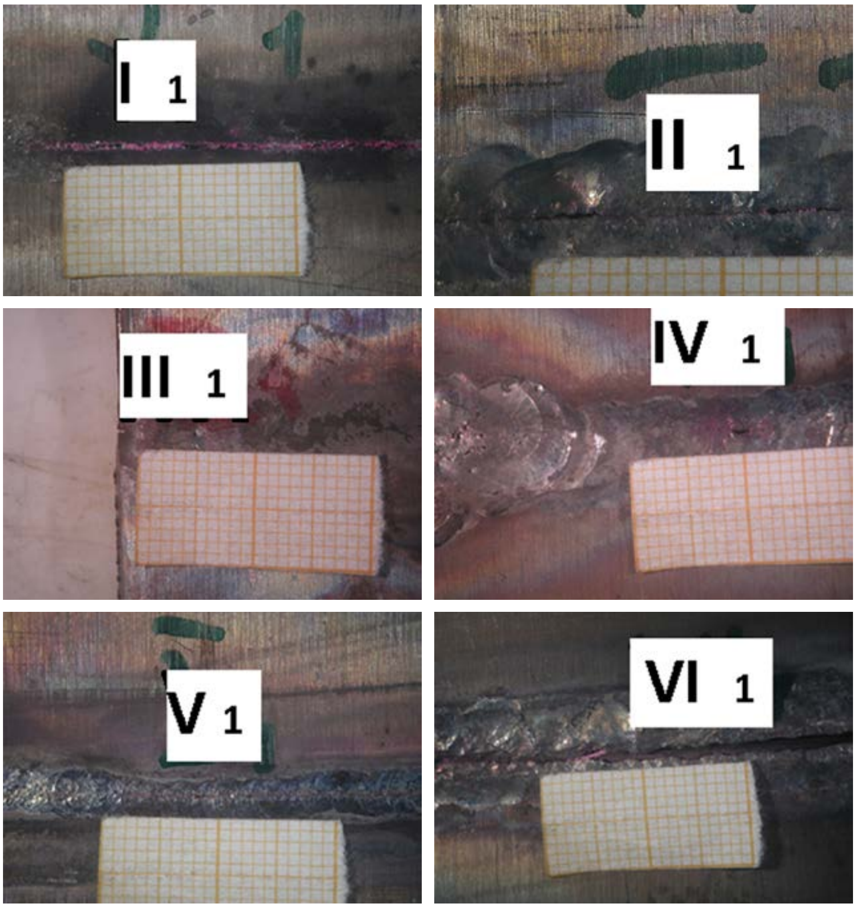

Fig. 3. Exemplary cracks in the butt joints made of nickel (magnified 4x). Roman numerals represent numbers of successive joints; Arabic numerals represent number of successive cracks in a given joint

referred to as the time of development, may vary from several minutes to even 24 hours. The objective of the investigation was to determine how the width of a crack and the roughness of its surface affect the time of development in welded joints made of nickel and its alloys and what time of development should be used in relation to these materials. In order to obtain more accurate results, the tests described in the article were performed using natural cracks [1-3].

Test Specimens

The tests involved the use of Nickel 200. The determination of crack widths involved making 6 butt joints (140×240×6 mm) (Fig. 2). The melting of plates nos. 5 and 6 was not followed by the formation of cracks. In order to solve this problem and create cracks, plates nos. 5 and 6 were cut at the area of melting and welded. The butt joints were welded using the TIG method without a filler metal. The test joints were provided with numerals.

Tests

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 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 and 4).

Macroscopic photographs of the cracks were made using an Olympus szx9 stereoscopic microscope at 4x and 28.5x magnification. 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.

Table 1. Designations and the width of the cracks in the butt joints made of Nickel 200

Number of joint	Crack number	Crack width, µm
I	1	8÷612
	2	28÷368
	3	4÷340
II	1	4÷456
III	1	4÷204
IV	1	4÷272
	2	4÷48
	3	4÷248
	4	4÷104
V	1	4÷684
VI	1	4÷1228

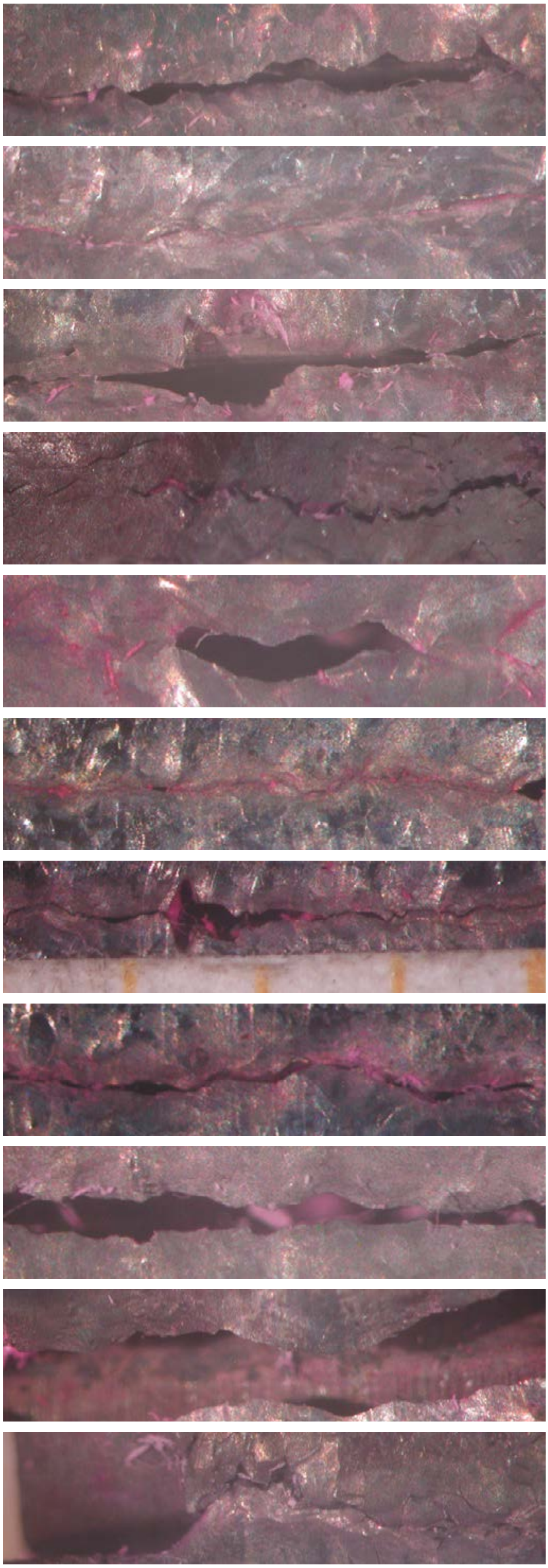
Fig. 4. Exemplary cracks in the butt joints made of nickel (magnified 28.5x)

The width of 11 measured cracks was restrained within the range of 4÷1228 µm. Before breaking, the crack areas (in order to measure the roughness profile of 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 standard Pn-en iso 3452-1, as IICe-2, type 'Diffu-Therm", 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 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, 90 and 120 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, where variables were the time of penetration and the time of development. The time of penetration amounted to 10, 30 and 120 minutes; the penetrant was applied several times so that a surface subjected to the tests was permanently covered by the penetrant. The different values of penetration time enabled examining the effect of the time of penetration on the time of development. On the basis of information contained in reference publications, the time of penetration was extended to 120 minutes, in comparison with recommendations of related standards, stating that the time of penetration should be restricted within the range of 5 to 60 minutes. The additional measurement was related to the time of development when the penetrant was applied only one time (90 minutes). The measurements of indications were conducted after 5, 10, 15, 20, 30, 40, 50 and 60 minutes etc., until the end of the development of a given indication (Table 2). Only one indication of the longest crack was recorded for each specimen. Each penetrant test was performed 3 times for specific parameters and the results were averaged.

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 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 5.

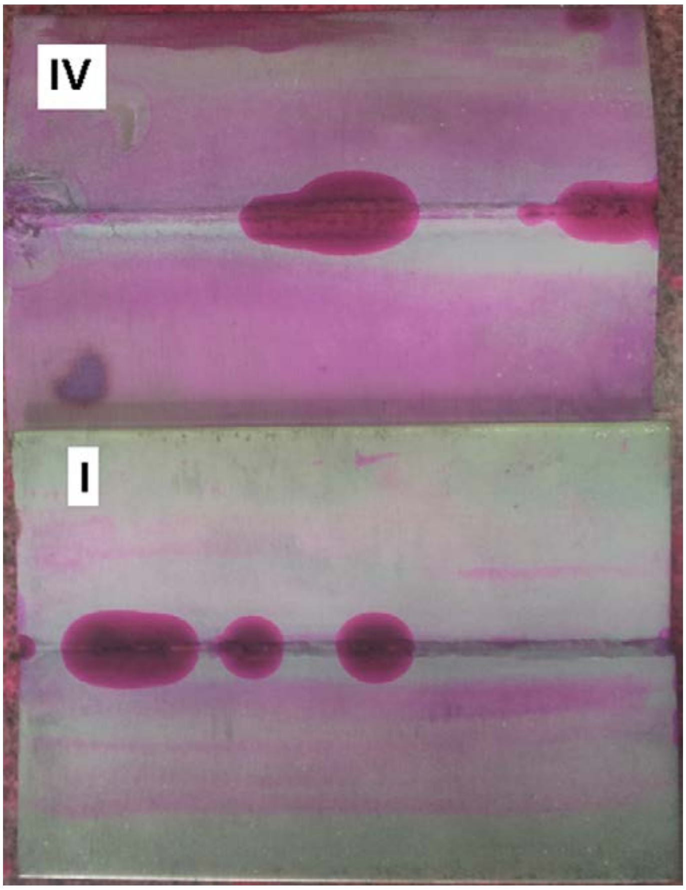

Fig. 5. Selected specimens made of nickel with indications originated in cracks. Roman numerals represent numbers of successive joints

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

Specimen no. I

Time of penetration, min	Development time, min																			
	5	10	15	20	25	30	40	50	60	70	80	90	100	110	120	140	170	200	230	260
10	40.5	42.0	43.5	44.5	46.0	47.5	48.5	49.5	51.0	52.0	52.5	53.0	53.5	54.0	54.5	55.0	56.0	-	-	-
30	40.0	42.0	43.5	45.0	46.0	47.5	49.0	50.0	51.5	52.0	52.5	53.0	53.5	54.5	55.0	56.0	57.0	57.5	-	-
120	39.0	41.0	42.5	44.0	45.5	47.0	48.0	49.0	50.0	51.0	52.0	52.5	53.0	53.5	54.0	55.0	56.0	57.0	57.5	-
90*	39.0	41.0	42.0	43.5	45.0	45.5	47.0	48.0	48.5	-	-	-	-	-	-	-	-	-	-	-

Specimen no. II

Time of penetration, min	Development time, min																			
	5	10	15	20	25	30	40	50	60	70	80	90	100	110	120	140	170	200	230	260
10	46.0	48.0	48.5	49.0	49.5	50.0	50.5	51.5	52.0	52.5	53.0	53.5	54.0	54.5	-	-	-	-	-	-
30	47.0	47.5	48.5	49.0	49.5	50.0	50.5	51.0	51.5	52.0	52.5	53.0	53.5	54.0	-	-	-	-	-	-
120	47.0	48.0	48.5	49.0	49.5	50.0	50.5	51.0	51.5	52.0	52.5	53.0	53.5	54.0	54.5	55.0	56.0	57.0	-	-
90*	47.0	48.0	48.5	49.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Specimen no. III

Time of penetration, min	Development time, min																			
	5	10	15	20	25	30	40	50	60	70	80	90	100	110	120	140	170	200	230	260
10	9.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
30	8.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
120	9.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90*	8.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Specimen no. IV

Time of penetration, min	Development time, min																			
	5	10	15	20	25	30	40	50	60	70	80	90	100	110	120	140	170	200	230	260
10	52.5	56.0	57.0	58.5	59.5	61.0	62.5	64.0	65.0	66.0	67.0	67.5	68.0	68.5	-	-	-	-	-	-
30	53.0	56.5	57.5	59.0	60.0	61.5	63.0	64.5	65.5	66.0	67.0	68.0	68.5	68.5	69.0	-	-	-	-	-
120	53.0	56.0	57.5	59.0	60.5	62.0	63.0	64.0	65.0	66.0	67.0	68.0	68.5	69.0	69.5	70.0	71.0	-	-	-
90*	59.0	59.5	60.0	60.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Specimen no. V

Time of penetration, min	Development time, min																			
	5	10	15	20	25	30	40	50	60	70	80	90	100	110	120	140	170	200	230	260
10	143.0	146.0	148.0	149.0	150.0	151.0	153.0	155.0	156.0	157.0	158.0	159.0	159.5	160.0	-	-	-	-	-	-
30	144.0	146.0	148.0	149.5	151.0	152.0	154.0	155.5	156.0	157.0	158.0	159.0	159.5	-	-	-	-	-	-	-
120	144.0	146.0	148.5	150.0	151.0	152.0	154.0	156.0	157.0	158.0	158.5	159.0	159.0	159.5	160.0	160.5	161.5	162.0	-	-
90*	143.0	146.0	148.0	149.0	150.0	151,0	152,0	-	-	-	-	-	-	-	-	-	-	-	-	-

Specimen no. VI

Time of penetration, min	Development time, min																			
	5	10	15	20	25	30	40	50	60	70	80	90	100	110	120	140	170	200	230	260
10	74.5	76.0	78.0	79.5	80.5	81.0	82.0	83.0	84.0	85.0	85.5	86.0	86.5	-	-	-	-	-	-	-
30	75.0	77.0	78.0	79.0	80.0	81.0	82.5	83.5	84.0	84.5	85.0	86.0	-	-	-	-	-	-	-	-
120	75.0	76.5	78.0	79.0	80.0	81.0	82.5	83.5	85.0	85.5	86.0	86.5	87.0	87.5	88.0	89.0	89.5	-	-	-
90*	77.0	78.0	79.0	80.5	81.0	81.0	81.5	82.5	84.0	-	-	-	-	-	-	-	-	-	-	-

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

The penetrant tests of the nickel specimens containing the cracks revealed that one of the objectives of the work had been satisfied. The tested differences in penetration time related to the joints made of nickel revealed that at longer penetration times (120 minutes) indications were greater, which could imply the necessity of extending both the time of penetration and the time of development in relation to these materials. Sometimes, at a shorter penetration time (10 minutes), the indications were slightly greater than those obtained at a penetration time of 30 minutes. Such differences rather demonstrated the specific nature of the test process itself as the process of penetrant testing consists of a number of phases, each of which must be performed paying significant attention to detail. Each negligence, usually unintended, in the testing process decreases its sensitivity, leading to the obtainment of a different final result. Knowing this, it is easy to explain detected inaccuracies, i.e. greater indications obtained at shorter penetration times. When the penetrant was applied once, the indications were significantly smaller and the time of development was shorter. It was also noticeable that in most of the cases, the size of indications grew dynamically up to approximately 15-20 minutes of development time. After this time, the increase in indications was very slow and in most of the cases finished after approximately 200 minutes (Fig. 6).

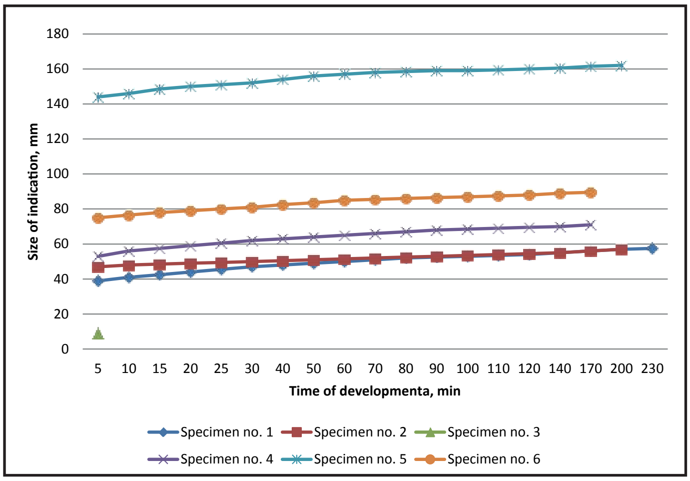

Fig. 6. Dependences between indication sizes and development times for the cracks formed in the joint made of nickel

This implies that when performing penetrant tests of joints made of nickel and its alloys, the time mentioned above can be recognised as adequate for detecting unallowed external imperfections (such as cracks). The tests also revealed a tendency that an increase in the width of a crack was accompanied by an increase in the time of development.

Another stage of the tests involved measurements of crack surface roughness. In order to determine profiles of roughness in the cracks, the butt joints were broken in the areas where the cracks were formed. 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. 7). 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).

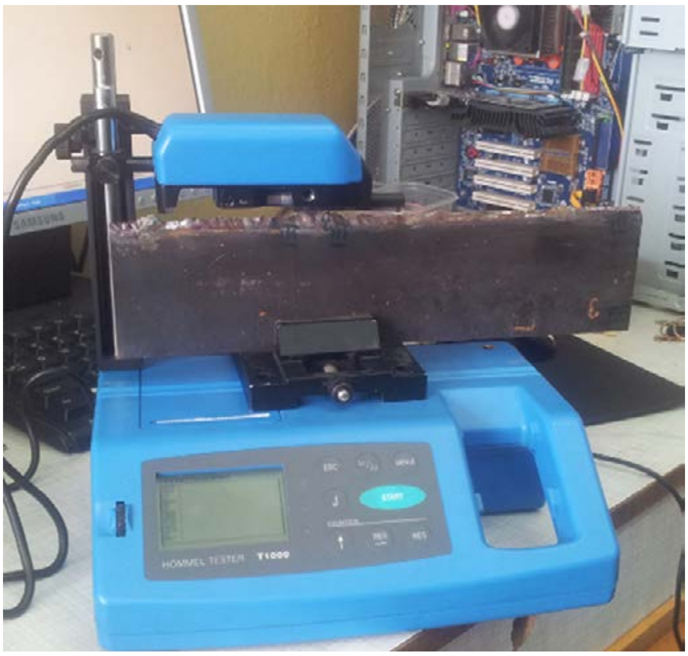

Fig. 7. Hommel tester T1000 contact profile measurement gauge

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. the surface profile and the roughness profile (Fig. 8).

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. 9).

The software programme integrated with the profile measurement gauge provides a lot of data concerning the surface being measured (Fig. 10). 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). Due to the shape of the joint surface after breaking, not all cracks could be measured.

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.

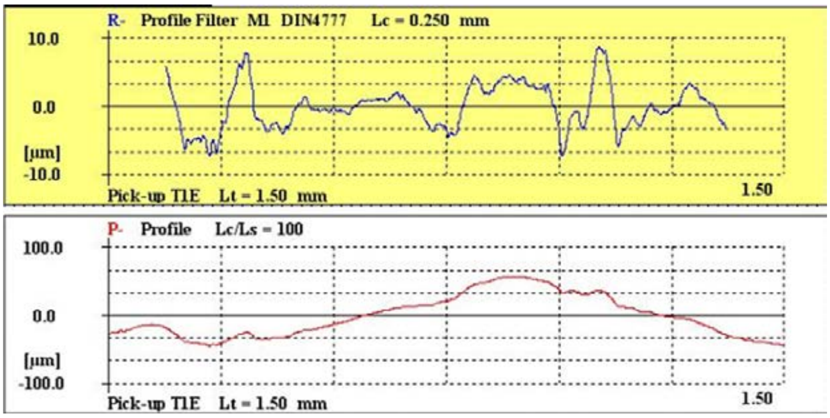

Fig. 8. Measurement of surface roughness (top) and of the profile (bottom)

Fig. 9. Visualisation of the stereometric structure of the surface being measured

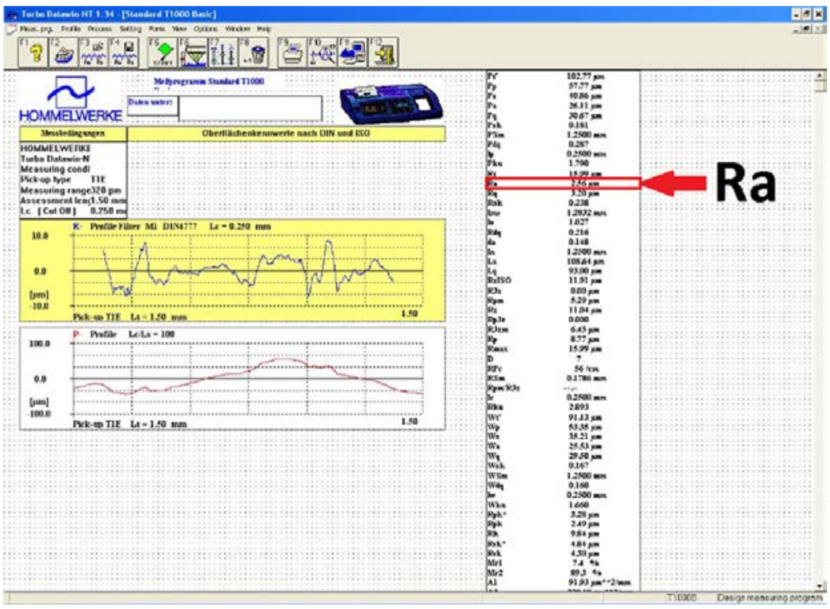

Fig. 10. Window of the Turbo Datawin-NT software programme. The red colour indicates parameter Ra (analysed in the work)

Table 3. Roughness of surfaces of the cracks detected in nickel Nickel 200

Plate/joint	I	I	I	II	III	IV	IV	IV	IV	V	VI
Crack	1	2	3	1	1	1	2	3	4	1	1
Roughness *Ra*, µm	3.98	4.57	5.15	2.41	2.61	7.40	1.39	2.56	3.40	1.66	4.00

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

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.

The roughness of crack surfaces was restricted within the range of 2.01 to 13.24. 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 a greater roughness of surface.

Conclusions

The analysis of the test results led to the formulation of the following conclusions:

1. As regards penetrant tests of nickel and its alloys, the time of penetration significantly affected times of development and sizes of indications and, therefore should be extended to 120 minutes.

2. In most cases, the single-time application of a penetrant resulted in a shorter development time and smaller-sized indications in comparison with situations when a penetrant was applied several times.

3. Each of the tested factors significantly affected development times in the penetrant tests, which was demonstrated by various development times in cases of various cracks.

4. An increase in the roughness of crack surface was accompanied by an increase in the time of development, which could probably be attributed to the greater spread of the surface and, as a result, the greater volume of penetrant located in a given discontinuity.

5. An increase in the width of a crack was accompanied by an increase in the time of development; this was because of the greater volume of penetrant in a given crack.

6. It is recommended that in penetrant tests of nickel and its alloys the time of development be extended to approximately 200 minutes. In most cases, such a time is sufficient for detecting unacceptable welding imperfections.

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References 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*