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

Abstract: The article presents welding imperfections, particularly the most dangerous of them, i.e. cracks, tested using the penetrant method. The tests involved making natural cracks in aluminium alloy AlSi1MgMn. Afterwards, the width of cracks and the profile of roughness were measured. The investigation also involved a series of penetrant tests performed in order to observe how a given factor (crack width, crack surface roughness) affects development times in penetrant tests involving joints made of aluminium and its alloys. The article also presents the determined development time recommended for aluminium and its alloys in order to detect indications originated in cracks as well as analyses penetration times in penetrant tests.

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

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Introduction

Welding processes are often accompanied by the formation of so-called welding imperfections, significantly deteriorating the strength of welded joints. The most dangerous imperfections include cracks, which, along with laps, folds, porosity and incomplete fusions (if they are open on the surface of materials being tested) can be detected using penetrant tests. Cracks constitute considerable concentrators of stresses and, due to their small dimensions, may remain undetected. For this reason, the successful detection of cracks using penetrant tests (e.g. dye or fluorescent) (Fig. 1) is of great

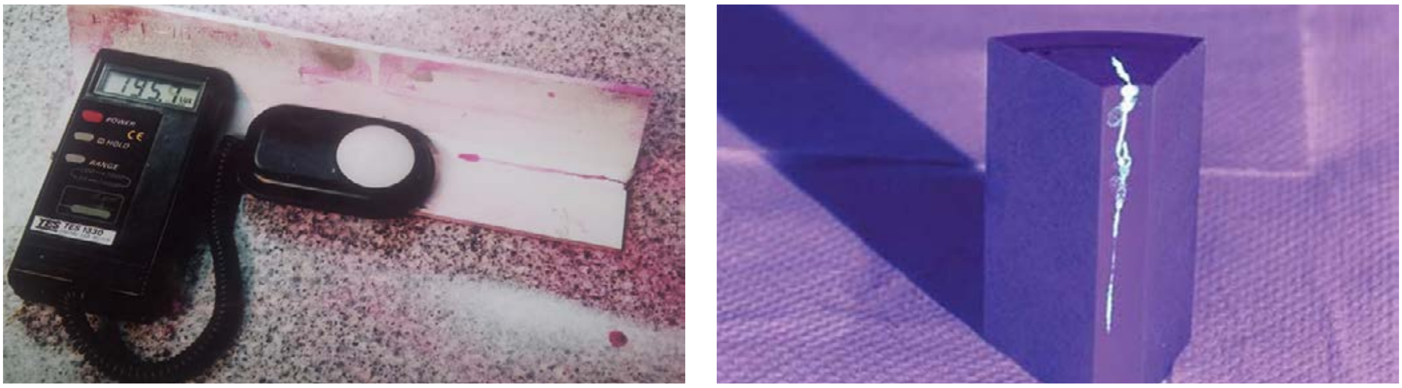

Fig. 1. Indications obtained during penetrant tests: a) using the dye penetrant method (observation of the surface in natural light), b) using the fluorescent method (observation of the surface in UV-A radiation)

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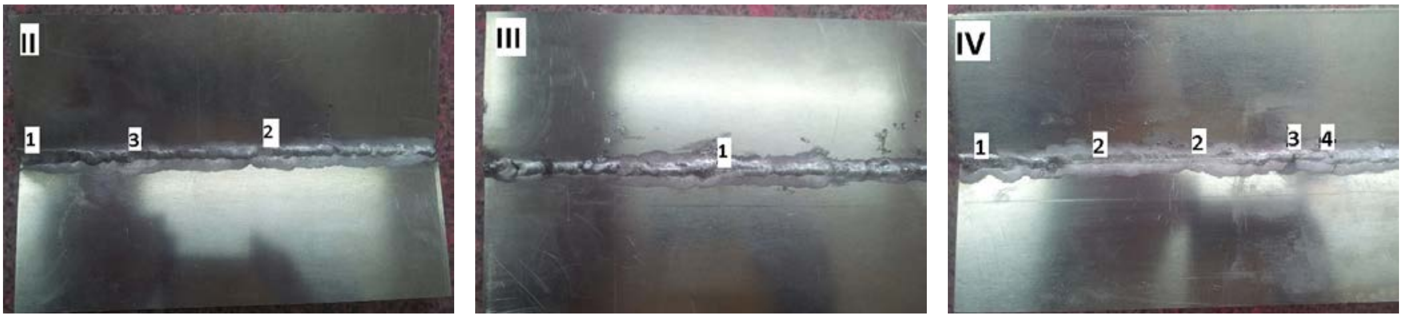

Fig. 2. Butt joints made of aluminium alloy AlSi1MgMn. Roman digits represent numbers of successive joints; Arab digits represent number of successive cracks in a given joint

importance. In penetrant tests, the time of development, i.e. the time after which a penetrant reaches the surface, 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 aluminium and its alloys. In order to obtain more accurate results, the tests described in the article were performed using natural cracks [1-3].

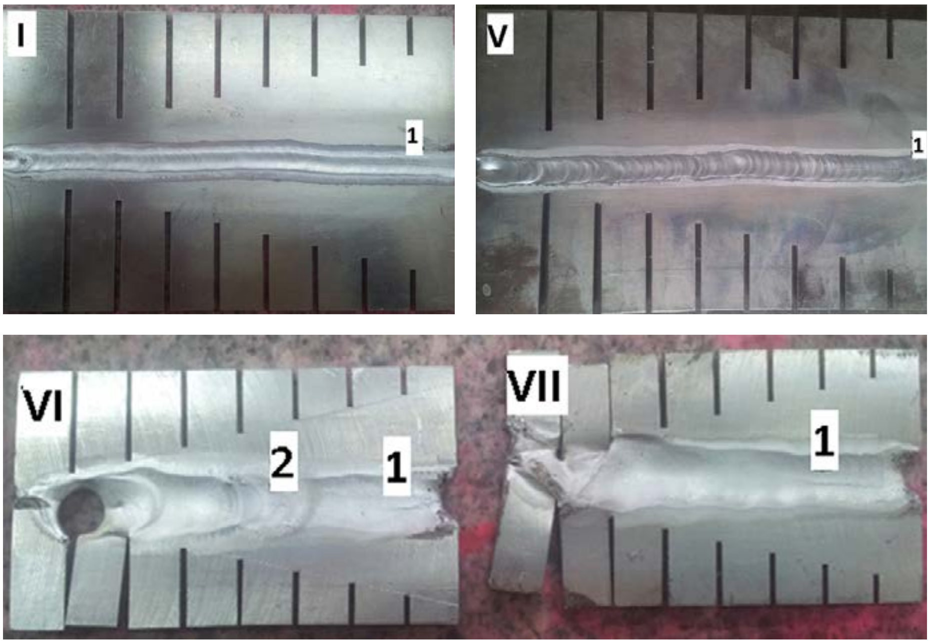

Fig. 3. Sheets with incisions after melting performed using the TIG method (visible cracks). Roman digits represent numbers of successive joints; Arab digits represent number of successive cracks in a given joint

Test Specimens

The tests involved the use of aluminium alloy AlSi1MgMn. The determination of crack widths involved making 3 butt joints (160×240×6 mm – 2 joints and 140×240×6 mm – 1 joint (Fig. 2) and 4 sheets with incisions. The butt joints were TIG welded using a filler metal in the form of a wire having a diameter of 1.2 mm. The filler metal was selected in accordance with recommendations specified in standard PN-EN 1011-4:2002/A1:2005 – AlMg4.5MnZr. The sheets with incisions, having dimensions

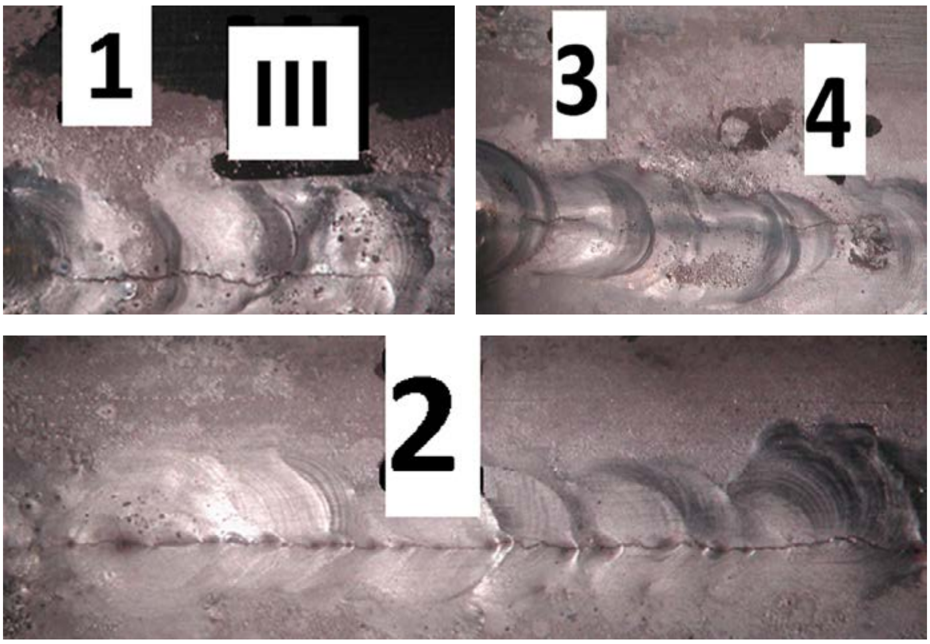

Fig. 4. Exemplary cracks in the welded joints made of aluminium alloy (magnified 4x). Roman digits represent numbers of successive joints; Arab digits represent number of successive cracks in a given joint

of 140×240×6 mm, 140×216×6 mm and 2 sheets having dimensions of 44×76×3 mm, were made in a manner similar to the Houldcroft's weldability test, also known as "the fishbone test", reflecting the hot crack susceptibility of a given material; the sheets were melted using the TIG method, in the manner presented in Figure 3.

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 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 and the sheets subjected to melting developed cracks (see Fig. 3 and 4).

Macroscopic photographs of the cracks were made using an Olympus SZX9 stereoscopic microscope (fig. 5) at 4x and 28.5x magnification (Fig. 6). The widths of the cracks were measured using an 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

Fig. 5. Olympus SZX9 stereoscopic microscope

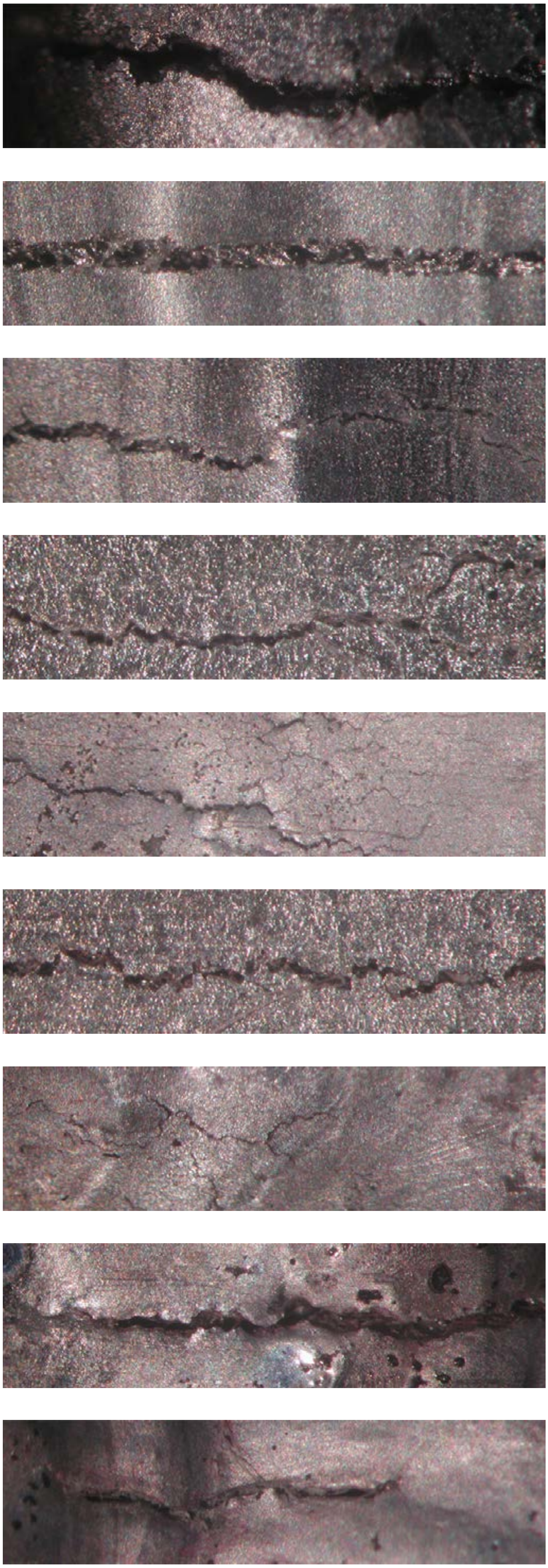

Fig. 6. Exemplary cracks in the welded joints made of aluminium alloy (magnified 28.5x)

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 and sheets subjected to melting are presented in Table 1.

The width of 13 measured cracks was restrained within the range of 4 μm to 472 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 (Fig. 7).

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 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°.

Table 1. Designations and the width of the cracks in the butt welded joints and sheets subjected to melting, made of aluminium alloy AlSi1MgMn

Number of joint/sheet	Crack number	Crack width, μm
I	1	4÷260
II	1	28÷76
	2	8÷36
	3	4÷48
III	1	8÷236
IV	1	4÷24
	2	8÷112
	3	40÷92
	4	4÷72
V	1	12÷472
VI	1	16÷192
	2	4÷32
VII	1	14÷108

Fig. 7. Set of aerosols "Diffu - Therm" used in the penetrant tests of the cracks

The penetrant tests of the cracks were performed using the dye penetrant method following the requirements of standard PN-EN ISO 3452-1. The tests involved all of the cracks in several tests, where variables were the time of penetration and the time of development. In accordance with standard PN-EN ISO 3452-1, the time of penetration should be restricted within the range of 5 minutes to 60 minutes. The tests were performed using penetration times of 10, 30 and 60 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). In order to limit the number of measurements, 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

Table 2. Sizes of indications originated in the cracks formed on the joints/sheets made of aluminium alloy. 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	52.0	53.0	54.0	54.0	55.0	56.0	56.5	57.0	57.0	58.5	58.5	59.0	59.0	59.0	59.5	60.0	-	-	-	-
30	53.0	54.0	55.0	56.0	56.5	57.0	57.0	57.5	58.0	59.0	60.0	60.0	60.5	61.0	61.5	62.0	-	-	-	-
60	52.5	53.0	54.0	55.0	56.0	57.0	57.5	57.5	58.0	59.5	60.0	60.5	60.5	60.5	61.0	61.0	-	-	-	-
60*	53.0	54.0	55.0	56.0	56.5	57.0	57.5	58.0	-	-	-	-	-	-	-	-	-	-	-	-

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	8.0	10.0	12.0	13.0	14.5	16.0	18.0	20.0	21.0	22.0	23.0	-	-	-	-	-	-	-	-	-
30	10.0	13.0	14.5	16.0	18.0	19.0	21.0	23.0	24.5	26.0	27.0	-	-	-	-	-	-	-	-	-
60	9.0	12.0	14.0	16.0	17.0	18.0	20.0	22.0	23.0	24.0	-	-	-	-	-	-	-	-	-	-
60*	10.0	12.0	13.5	14.5	15.5	16.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-

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	14.0	20.0	22.0	24.0	26.0	27.5	29.0	30.0	31.0	32.0	33.0	-	-	-	-	-	-	-	-	-
30	13.0	19.0	21.0	23.0	25.0	26.5	28.0	29.0	30.0	31.0	-	-	-	-	-	-	-	-	-	-
60	15.0	21.0	22.5	24.0	26.0	27.0	29.0	30.0	31.0	32.0	33.0	-	-	-	-	-	-	-	-	-
60*	14.0	19.0	22.0	23.0	23.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

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	111.0	113.0	115.0	116.0	117.0	118.0	186.0	187.0	188.0	189.0	190.0	-	-	-	-	-	-	-	-	-
30	111.0	112.0	114.0	115.0	116.0	117.0	184.0	185.0	186.0	186.0	187.0	-	-	-	-	-	-	-	-	-
60	110.0	112.0	113.0	114.0	115.0	116.0	180.0	181.0	181.0	182.0	183.0	-	-	-	-	-	-	-	-	-
60*	110.0	112.0	113.0	114.0	114.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

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	83.0	83.5	84.0	85.0	85.5	86.0	87.0	88.0	88.0	88.5	89.0	90.5	91.0	91.0	91.5	92.0	92.5	93.0	-	-
30	84.0	84.5	85.0	85.0	86.0	86.5	87.5	88.0	88.5	89.0	89.5	90.0	90.5	91.0	91.5	92.0	92.5	93.0	-	-
60	80.0	81.0	82.0	83.0	84.0	85.0	86.5	87.0	87.5	88.0	88.5	89.0	89.5	90.0	90.5	91.0	91.5	92.0	-	-
60*	82.0	83.0	84.0	84.5	85.0	85.5	86.0	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 2 – continuation

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	9.0	10.0	11.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
30	13.0	14.0	15.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	11.0	12.0	13.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60*	12.0	13.0	14.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Specimen no. VII																				
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	21.0	22.0	23.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
30	20.0	21.0	22.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	20.0	21.0	22.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60*	21.0	22.0	23.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

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

more accurate determination of the dependence being the subject of this work and the dynamics of crack formation. The adopted time of indication development exceeded the recommendation 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 8.

The penetrant tests of the aluminium 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 aluminium did not significantly affect the time of development, but rather demonstrated the specific nature of the test process itself. 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. During the tests it was also noticeable that in most of the

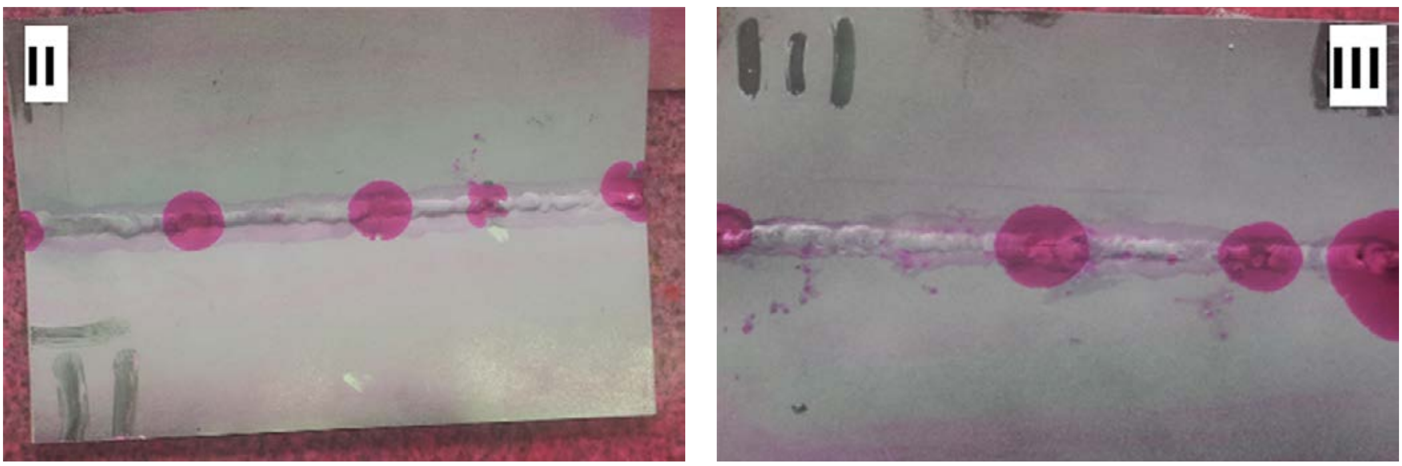

Fig. 8. Selected specimens made of aluminium alloys with indications originated in cracks. Roman digits represent numbers of successive joints

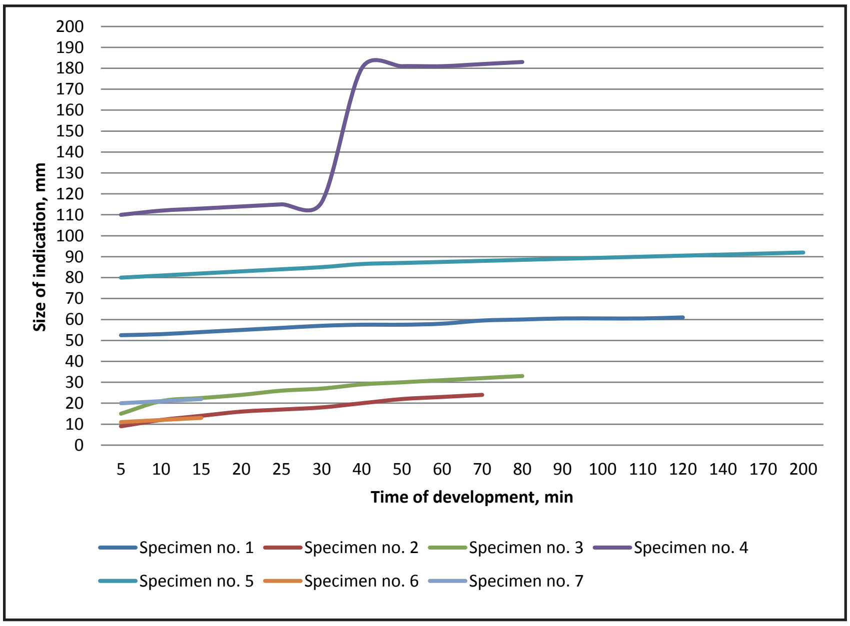

Fig. 9. Dependences between indication sizes and development times for the cracks formed in the aluminium alloy

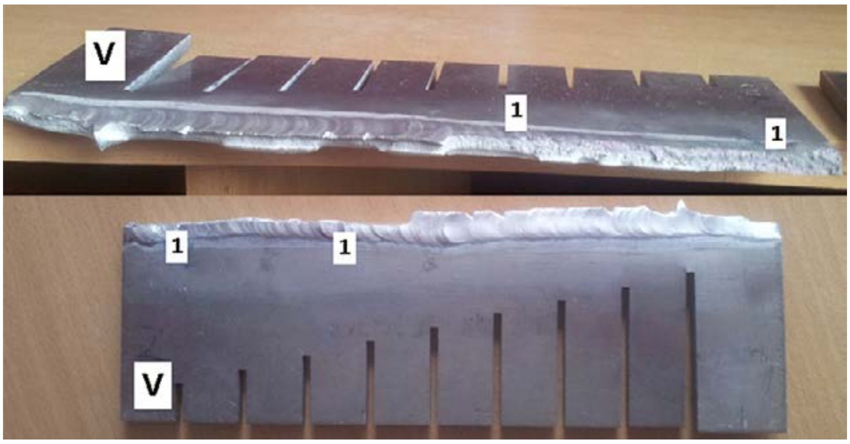

Fig. 10. Butt joint made of aluminium alloy after breaking in the crack formation area. Roman digits represent numbers of successive joints; Arab digits represent number of successive cracks in a given joint

Fig. 11. Hommel tester T1000 contact profile measurement gauge

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 80 minutes (see the diagram in Figure 9). This implies that when performing penetrant tests of joints made of aluminium 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 roughness of a crack surface and in the crack width was accompanied by an increase in the time of development. The significant increase in the length of indication observed in relation to specimen number 4 resulted from the combination of two indications. Another stage of the tests involved measurements of crack surface roughness. In order to determine profiles of roughness in the cracks, the sheets and the butt joints were broken in the areas where the cracks were formed (Fig. 10). 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. 11). 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),
- roughness core parameters (Rk),
- parameters of the motif-detection method (WD1 and WD2).

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 was made to measurements, i.e. of the surface profile and the roughness profile (Fig. 12).

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. 13).

The software programme integrated with the profile measurement gauge provides a lot of data concerning the surface being measured (Fig. 14). 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 lr amounted to 0.8 mm or 2.5 mm, whereas the length of measurement segment lt 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. The roughness of crack surfaces was restricted within the range of 2.01 to 13.24.

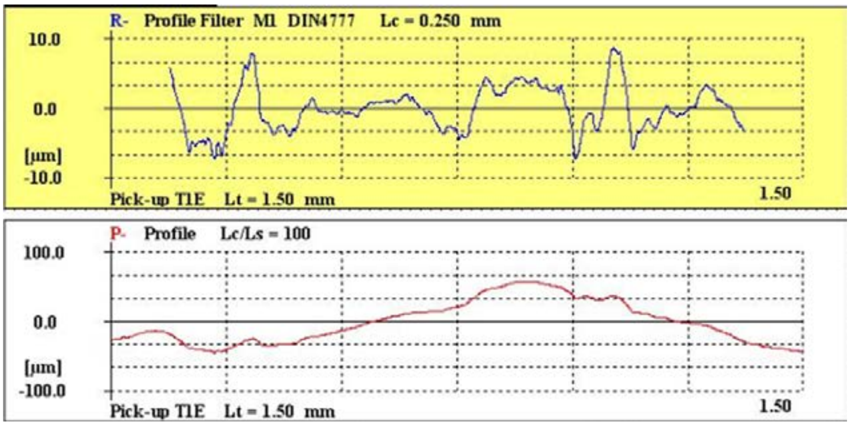

Fig. 12. Measurement of surface roughness (top) and of the profile (bottom)

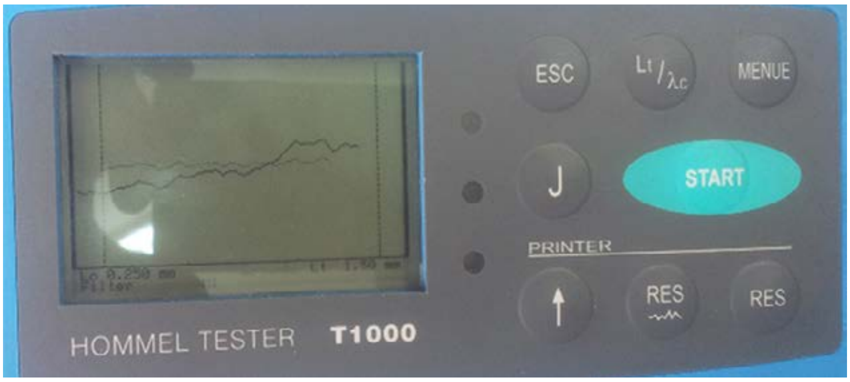

Fig. 13. Visualisation of the stereometric structure of the surface being measured

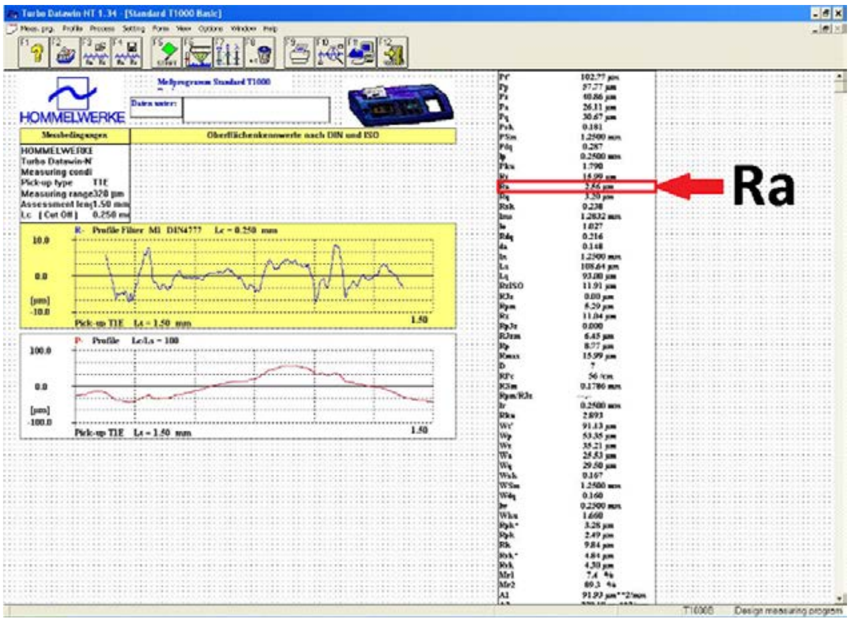

Fig. 14. Window of the Turbo Datawin-NT software programme. The red colour indicates parameter Ra (analysed in the work)

Table 3. Roughness of surfaces of the cracks detected in aluminium alloy AlSi1MgMn

Sheet/joint	I	II	II	II	III	IV	IV	IV	IV	V	VI	VI	VII
Crack	1	1	2	2	1	1	2	3	4	1	1	2	1
Roughness Ra, µm	13.24	5.23	4.65	2.05	4.08	2.01	6.25	5.78	3.28	9.14	5.59	8.37	6.37

Notice: Roman digits represent numbers of successive joints; Arab digits represent number of successive cracks in a given joint

Conclusions

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

1. As regards penetrant tests of aluminium and its alloys, the time of penetration did not significantly affect times of development and sizes of indications and could amount to a mere 10 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 aluminium and its alloys the time of development be extended to approximately 80 minutes. In most cases, such a time is sufficient for detecting unacceptable welding imperfections.

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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*