Karolina Poch, Ryszard Krawczyk, Jacek Słania

The Analysis of Parameters of Magnetic Tests in Respect of Quality Assessment of T-Joints with Fillet Welds

Abstract: Welded joints with fillet welds constitute the majority of joints made in various structural elements. The crucial role of such joints is emphasized particularly in respect of structural quality control. The primary issue "troubling" T-joints with fillet welds is the lack of penetration in surfaces of elements, i.e. the welding imperfection affecting the strength of joints in service conditions. Joints containing fillet welds are usually tested using surface methods, which significantly limits appropriate assessment and does not ensure the detection of volumetric imperfections. The article discusses the magnetic particle test-based detectability of volumetric imperfections in T-joints with fillet welds. Magnetic particle tests provide extensive possibilities as regards the assessment of structural elements, including welded joints containing poorly detectable discontinuities. Particular attention should be paid to T-joints with fillet welds. The analysis of test results made it possible to identify test parameters and conditions enabling the detection of lacks of penetration. In addition, the analysis revealed the correlation between test parameters and dimensions of joints as well as enabled the determination of magnetic field intensity-related boundary conditions making it possible to obtain indications of discontinuities in T-joints with fillet welds.

Keywords: non-destructive tests, magnetic particle tests, quality control, welded joints, lack of penetration

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Introduction

Along with the developmental progression of technologies, non-destructive tests (NDT) become increasingly important and, at the same time, face increasingly high challenges necessitated by the knowledge concerning the actual quality of manufactured products. An important aspect of non-destructive tests results from their non-invasive nature and repeatability when examining the structure and properties of elements [1, 2]. One of the well-known and widely used methods of non-destructive tests are magnetic particle tests, playing an important role in the verification of the quality of welded joints at individual stages of fabrication and subsequent operation. The above-named tests

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are widely used in the examination of structural elements and welded joints characterised by poorly detectable discontinuities [3–5].

Characteristics of T-joints with fillet welds

Because of easy preparation and fabrication as well as low fabrication costs, fillet welds constitute a large number of joints made in welded structures and elements. The crucial role of fillet welds is emphasized in terms of structure quality control. Some of the primary problems concerning T-joints with fillet welds are lacks of penetration [9, 10], both in terms of the upper sheet corner and as regards the surfaces of elements joined using fillet welds. In the PN EN ISO 6520-1 standard, the above-presented imperfections are classified as incomplete fusion (401) and the lack of penetration (4021) [16].

Joints with fillet welds are usually tested using surface methods, which significantly limits their appropriate assessment and does not ensure the detectability of volumetric imperfections.

T-joints with fillet welds are usually made using the MAG or TIG methods. The making of a T-joint with a fillet weld consists in the joining of two edges of elements. The weld is made in a natural groove, formed between the walls of elements being joined. Effective fillet weld thickness *a* is the height of the largest triangle inscribed in the outline of the weld cross-section, measured perpendicularly to the external side of the triangle [9]. A T-joint with a fillet weld is presented in Figure 1.

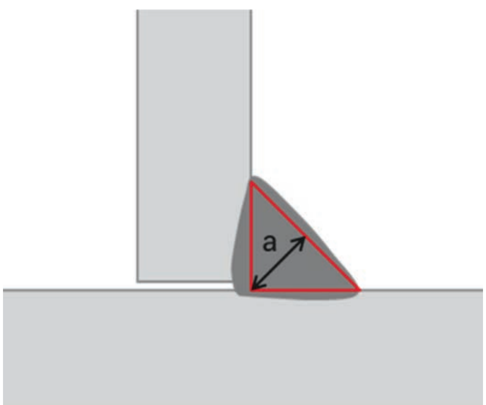

Fig. 1. T-joint with the fillet weld and dimension *a*

In respect of the detectability of lacks of penetration in fillet joints involving the use of the magnetic particle testing method, it is dimension *a* that plays an important role. Taking into account the aforementioned conditions, dimension $a \leq 3$ mm if test results are to be effective. The above-presented value is the ultimate limit where the sensitivity of the magnetic particle testing method guarantees the obtainment of indications of imperfections.

The crucial role of T-joints in welded structures

In comparison with butt-welded joints and in terms of quality inspection, T-joints are more difficult to assess as regards the presence of volumetric imperfections. The aforesaid difficulties may result in failure to detect serious welding imperfections such as lacks of penetration, which, in turn, could become of key importance as regards the evaluation of the entire structure. The foregoing could result in the direct loss of stability, particularly in cases where a given structure is exposed to variable loads.

The role played by T-joints with fillet welds in welded structures was the main reason for an attempt to assess the usability of the magnetic particle testing method in detecting lacks of penetration.

The strength and service life of welded structures depend on numerous factors and correlations between them. The above-named factors are the following:

- properties of base materials and filler metals,
- heat treatment and the operating temperature of a given structure,
- internal stresses and types of loads,
- size, types and locations of welding imperfections in joints.

When considering the last factor, i.e. welding imperfections, it should be stated that they have a crucial effect on the quality of welded joints as the presence of imperfections affects primarily the mechanical strength of joints. The presence of subsurface imperfections is connected with the depleted volume of joints [11]. Each imperfection, such as incomplete fusion, the lack of penetration, porosity or an undercut, decreases the volume of a given joint and, consequently, reduces its mechanical properties. In addition, all too often internal imperfections initiate fatigue cracks and, as a result, lead to the loss of load-carrying capacity triggered by the presence of fatigue stresses. There have been cases of construction disasters triggered by the aforesaid imperfections. In addition, it can be stated that the loss of load-carrying capacity triggered by fatigue or brittle cracking is significantly more common in structures which were subjected to insufficient inspection during welding works.

Penetration in T-joints with fillet welds

T-joints with fillet welds play a very important role in the transfer structural loads and, because of that, the quality of such joints is of utmost importance. The obtainment of proper penetration has an undoubtedly significant effect on the structural strength of the joint [9]. The properly made T-joint with the fillet weld as well as common imperfections, i.e. the lack of penetration and incomplete fusion are presented in Figure 2.

It should also be emphasized that the obtainment of proper joints is often difficult and requires both proper welding process parameters and appropriate welder's skills.

T-joints are usually made using MAG, TIG or MMA welding methods. The tests discussed in the article involved the use of the MAG method. The MAG welding process is widely used in civil engineering, power engineering, machine-building, maritime and other industries. The MAG method, enabling the welding of both thin and thick-walled elements, is regarded as an efficient and universal technique making it possible to obtain welds in various elements and welding positions. In terms of the MAG method, important process parameters include welding current, arc voltage and the appropriate diameter of the filler metal wire. The obtainment of proper penetration requires the selection of an appropriate welding position and the use of an appropriate welding torch handling technique [10].

MAG welding can be performed as a single or multi-run process, which, in cases of magnetic particle tests, is important in terms of weld dimension *a*.

Detectability of lacks of penetration in magnetic particle tests

Taking into account the above-presented technological factors, the authors attempted to use magnetic particle tests to detect lacks of penetration in T-joints with fillet welds. To this end, it was necessary to perform many simulations and analyses. The tests were performed using special standard specimens, designed and made in accordance with a schematic diagram presented in Figure 3.

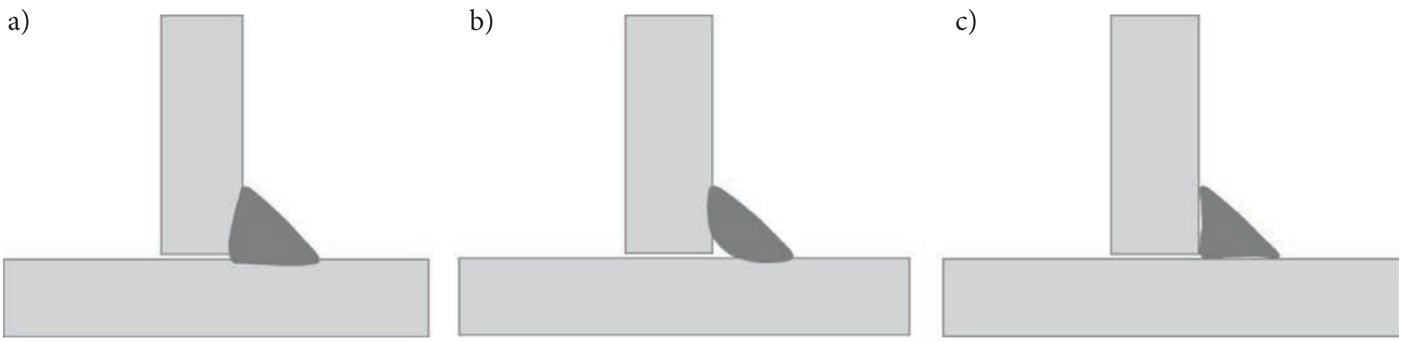

Fig. 2. T-joint with the fillet weld: a) proper penetration, b) lack of penetration and c) incomplete fusion

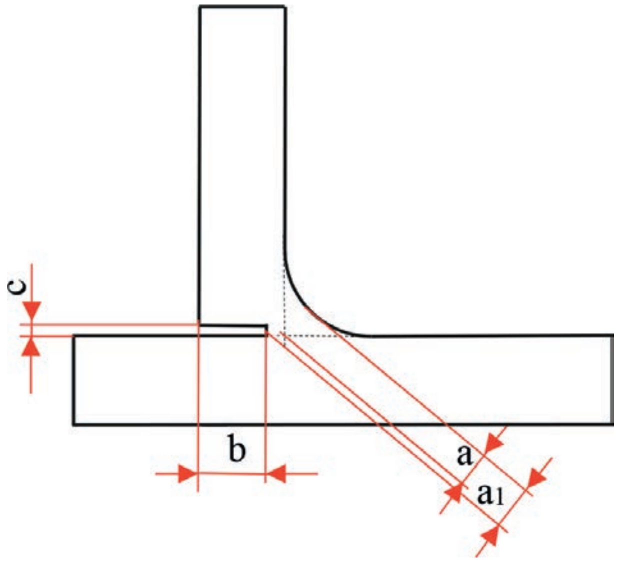

Fig. 3. Schematic diagram of the standard specimen, where a – fillet weld dimension, a_1 – distance between the weld face and the bottom of the incision, b – incision depth and c – incision width

Standard specimens of T-joints with fillet welds and ultimate limit dimensions make it possible to characterised appropriate indications. The standard specimens consisted of double T-bars HEB100 made of popular ferritic steel S235JR, characterised by favourable weldability and used in welded structures. Steel S235JR belongs to magnetically soft materials characterised by very good magnetic properties. In order to obtain the appropriate value of induction, the magnetically soft material should be affected by a low-intensity field. In addition, magnetically soft materials are characterised by higher magnetic permeability, which is an important factor during the magnetisation of materials.

An imperfection simulated in the standard specimens had the form of a 0.25 mm thick incision along the entire length of the joint. The incision was made in several variants. An incision parameter variable was the distance between the bottom of the incision and the face of the simulated weld, i.e. dimension a_1. In individual standard specimens, the dimension of simulated filler weld a = 2 mm was constant, whereas the value of distance a_1 changed and was as follows:

- standard specimen no. 1: a_1 = 4 mm (simulation at the ultimate detection sensitivity in the magnetic particle testing method),
- standard specimen no. 2: a_1 = 3 mm (simulation of proper penetration having a depth of 1 mm)
- standard specimen no. 3: a_1 = 2 mm (simulation at the verge of penetration),
- standard specimen no. 4: a_1 = 1 mm (simulation of the significant lack of penetration).

Because of the size of the standard specimens, in order to obtain proper test results, it was necessary to apply magnetisation in the coil with parameters of the magnetic field having intensity H = 0.8 kA/m. Higher values of magnetic field intensity lead to supersaturation (in a given element), resulting in the lack of indications and ambiguous test results. The foregoing revealed that the range of magnetic field intensity was not explicit in relation to all types and sizes of welded joints and should be adjusted individually for each element in relation to its dimensions.

Tests involving standard specimens nos. 1 through 4 led to the obtainment of indications presented in Figure 4 a–d.

The induction of the magnetic field in the test specimens was performed using an electromagnetic coil composed of a power supply unit featuring the continuous adjustment of magnetising current up to 1500 A as well as a three-turn coil having a diameter of 220 mm and a winding length of 140 mm. The testing station is presented in Figure 5.

The tests involving the standard specimens revealed the existence of strict correlations between the intensity of indications and the distance from the test surface, which provided the basis for the obtainment of effective results concerning penetration in fillet welds. The tests aimed to verify the method as regards the possibility of assessing the penetration of the first run of the fillet weld having dimension $a \leq 3$ mm. The first run (the so-called penetration run) is very important in terms of the proper quality

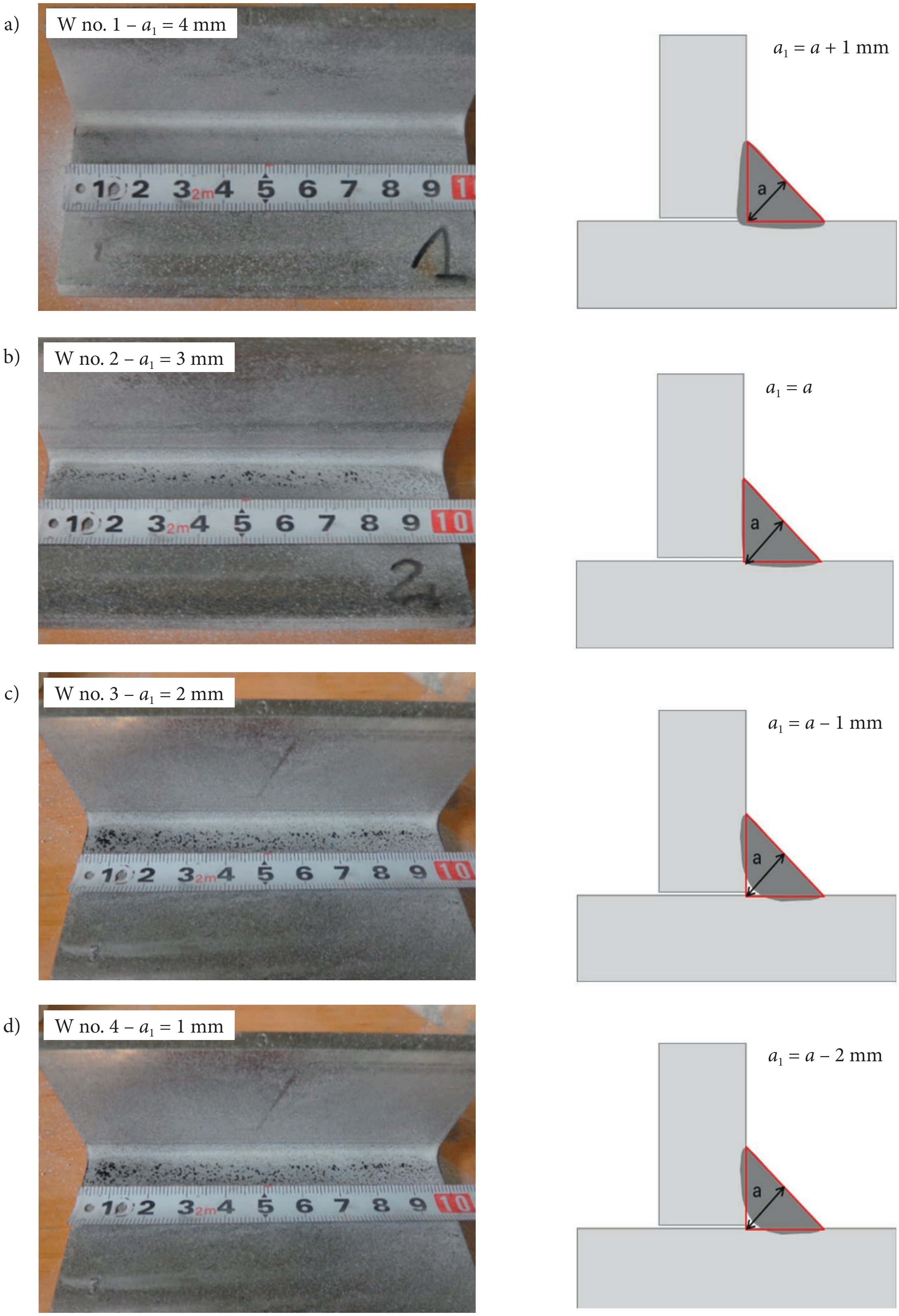

Fig. 4. Indications revealed in standard specimens nos. 1 through 4 along with the illustration of the simulated discontinuity in the T-joints: a) simulation at the ultimate detection sensitivity in the magnetic particle testing method, b) simulation of proper penetration having a depth of 1 mm, c) simulation at the verge of penetration and d) simulation of the significant lack of penetration

Fig. 5. Magnetic particle testing station with the electromagnetic coil

of the joint and its strength. The elimination of discontinuities at this stage is very important as it reduces the potential defectiveness of the joint. Because the remaining runs are easier to make, the probability of the formation of welding imperfections from group 4 is lower.

Tests involving standard specimens eliminate any doubts concerning the actual welding process, which is very complicated and depends on numerous external conditions, significantly affecting the quality of the joint. The designed standard specimen should reflect actual conditions obtainable at subsequent stages of tests (aimed to verify process repeatability).

It should be noted that until recently it has been possible to detect internal imperfections in T-joints with fillet welds using radiographic (RT), ultrasonic (UT) and macroscopic destructive tests. However, the volumetric RT and UT methods require the application of complicated techniques and special testing procedures. In terms of radiographic tests it is necessary to make several exposures, whereas in cases of ultrasonic tests it is necessary to perform many scans using several transducers of very narrow scanning ranges [12]. The above-presented factors make tests aimed to detect imperfections from group 4 very expensive, which significantly reduces the usability of the aforesaid testing techniques. The magnetic particle testing method makes it possible to detect imperfections from group 4 (under specific test conditions), without using expensive testing solutions and breaking the structure of a given element.

Parameters and conditions of tests involving T-joints with fillet welds

The assessment of sensitivity in T-joint subjected to magnetic particle tests required the performance of a series of tests involving joints with simulated discontinuities (i.e. lack of penetration). The length of the discontinuity amounted to 160 mm; the imperfection was located 20 mm away from the beginning and 20 mm away from the end of the weld (see Figure 6). The effect of the lack of penetration was obtained by incising the lower edge of the vertical sheet along a length of 160 mm and the subsequent making of a single-run weld using the MAG method in the vertical down position (PG). In the aforesaid manner it was possible to obtain the effect of the lack of penetration along a specific length of the joint.

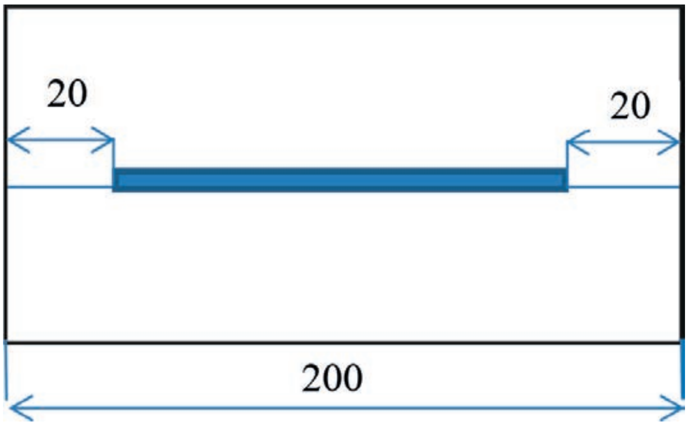

Fig. 6. Schematic diagram presenting the location of the simulated discontinuity in the joint

The assessment of sensitivity was based on a series of tests involving the same test specimen and various values of magnetic field intensity adjusted using an electromagnetic coil having tangent field intensity restricted within the range of 1.5 kA/m to 5 kA/m (taking into account recommendations contained in reference publications) [13–16]. The values of electromagnetic field intensity used in the assessment of the joint changed every 0.5 kA/m. The above-named values were identified on the basis of previously performed tests (during which indications of existing discontinuities were obtained).

The indications obtained during tests performed in the magnetic field are presented in Figures 7–14.

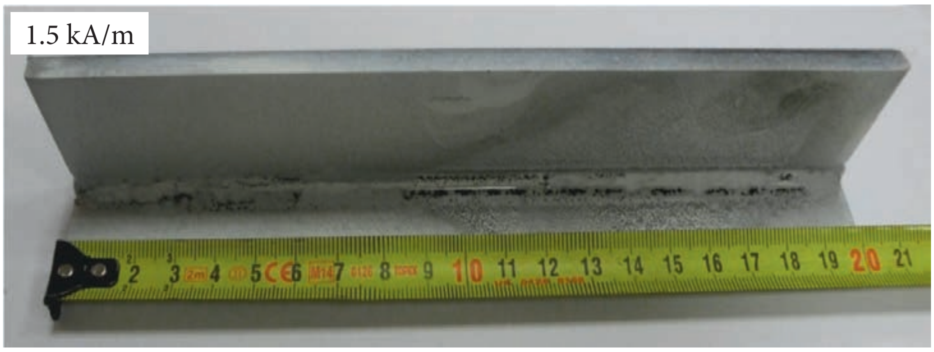

Fig. 7. Indications obtained in relation to a magnetic field intensity of 1.5 kA/m

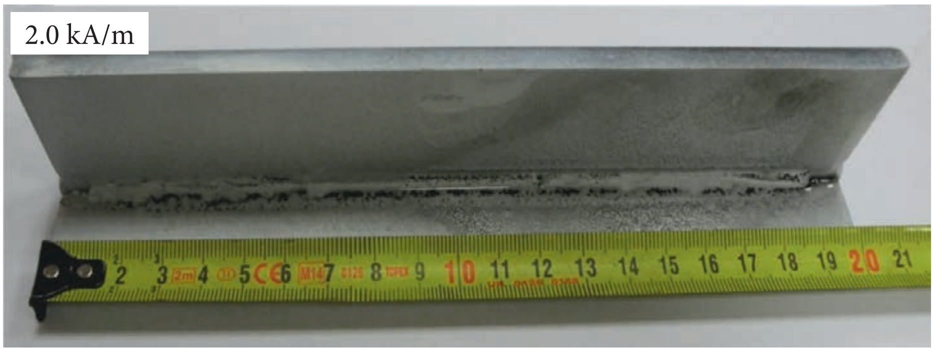

Fig. 8. Indications obtained in relation to a magnetic field intensity of 2.0 kA/m

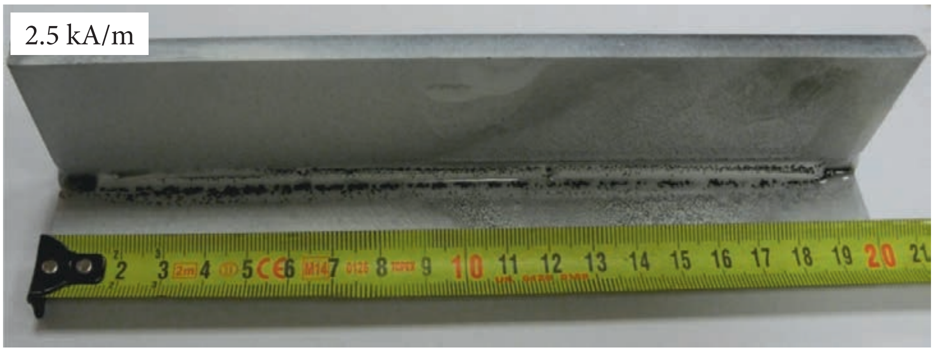

Fig. 9. Indications obtained in relation to a magnetic field intensity of 2.5 kA/m

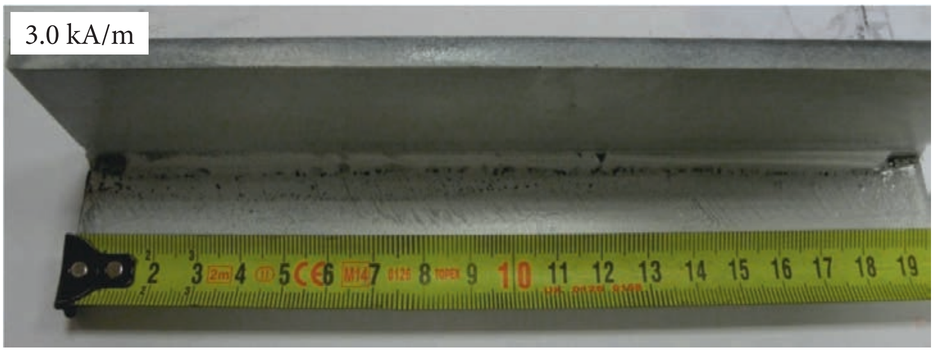

Fig. 10. Indications obtained in relation to a magnetic field intensity of 3.0 kA/m

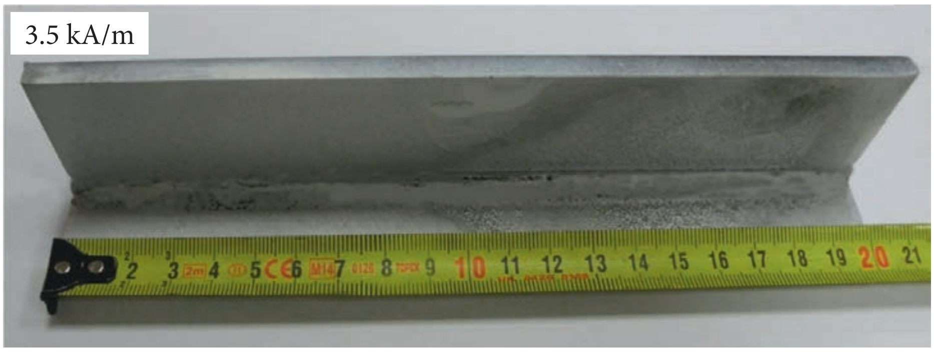

Fig. 11. Indications obtained in relation to a magnetic field intensity of 3.5 kA/m

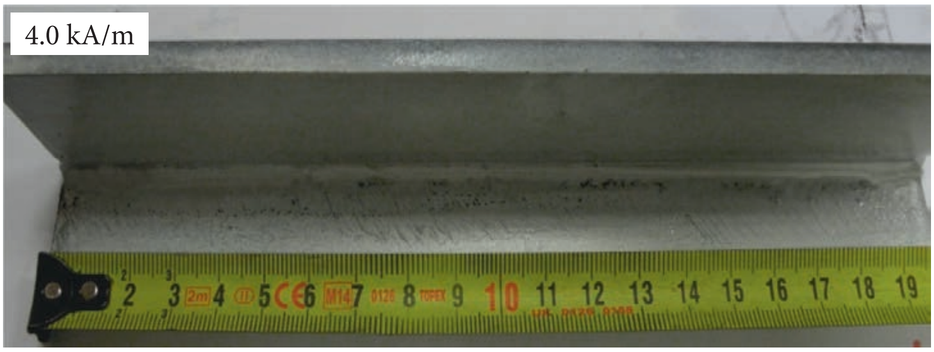

Fig. 12. Indications obtained in relation to a magnetic field intensity of 4.0 kA/m

Fig. 13. Indications obtained in relation to a magnetic field intensity of 4.5 kA/m

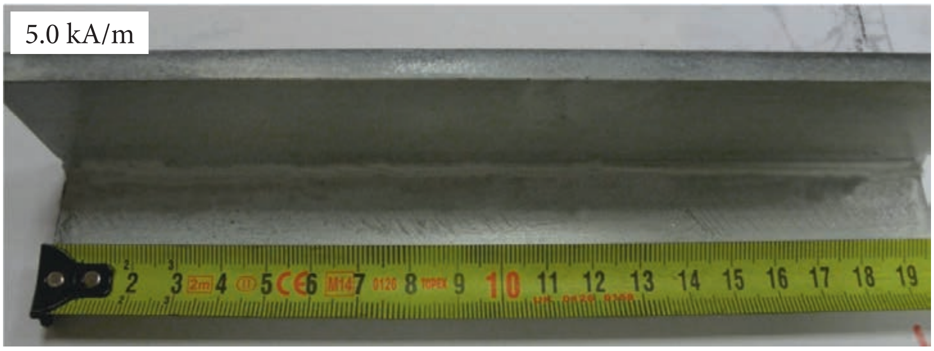

Fig. 14. Indications obtained in relation to a magnetic field intensity of 5.0 kA/m

The indications presented in subsequent Figures, i.e. 7 through 14, confirmed that the most effective tests results were obtained when magnetic field intensity was restricted within the range of 2.0 kA/m to 2.5 kA/m. The indications obtained in the tests overlapped with the lower limit of the range recommended in related reference publications. In the remaining cases it was possible to observe a certain tendency, where an increase in magnetic field intensity was accompanied by a clearly visible and significant decrease in indication intensity. As stated in reference publications, there were no indications in relation to values close to the upper limit. The foregoing could imply the supersaturation of the tested material with the magnetic field and, consequently, the lack of revealed indications of magnetic stray fields. An additional conclusion could be that the value of magnetic field intensity should be adjusted in relation to the size and thickness of an element being tested; the smaller the element, the smaller the range of magnetic field intensity should be applied.

The results obtained in the above-named series of tests are presented in Table 1 as well as in Figures 15 and 16.

The variability of the function presented in Figure 15 made it possible to identify testing sensitivity in relation to applied magnetic field intensity. Within the range of 1.5 kA/m to 2.0 kA/m, the indications obtained in the tests were characterised by low sensitivity. In turn, within the range of 2.0 kA/m to 2.5 kA/m (of applied

Table 1. Indications obtained in relation to various values of magnetic field intensity

Value of magnetic field intensity *H*, kA/m	Length of indication, mm	Intensity of indication
1.5	100	Very intense indication along a length of 50 mm, the remaining length of the indication slightly less intense, yet visible and at the level of assessment: grouped indication
2.0	170	Very intense indication along a length of 120 mm, the remaining length of the indication visible and at the level of assessment: grouped indication
2.5	165	Very intense indication along a length of 140 mm, the remaining length of the indication visible, grouped indication
3.0	50	Indication visible along a length of 50 mm, 100 mm away from the beginning of the weld
3.5	20	Low-intensity indication, visible along a length of 20 mm, 100 mm away from the beginning of the weld
4.0	0	Lack of indication
4.5	0	Lack of indication
5.0	0	Lack of indication

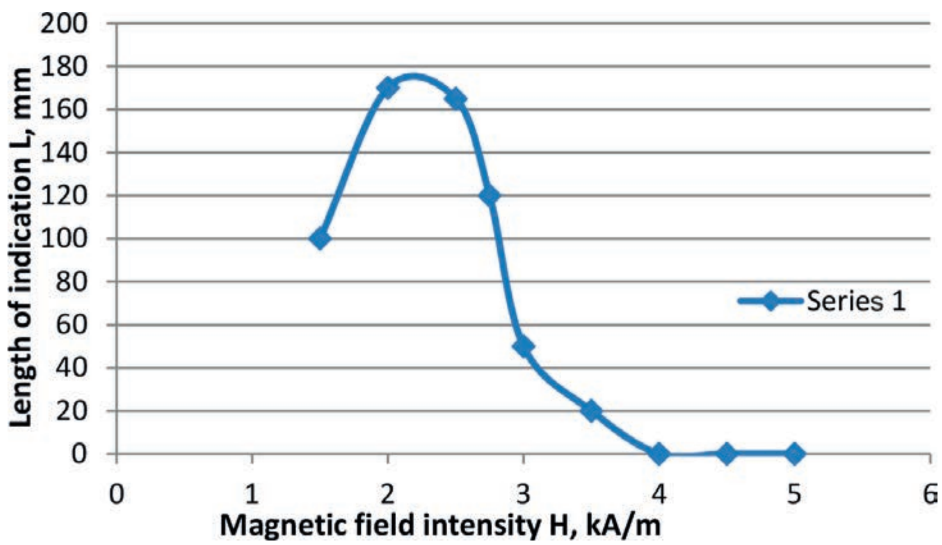

Fig. 15. Correlation between lengths of indications and values of magnetic field intensity

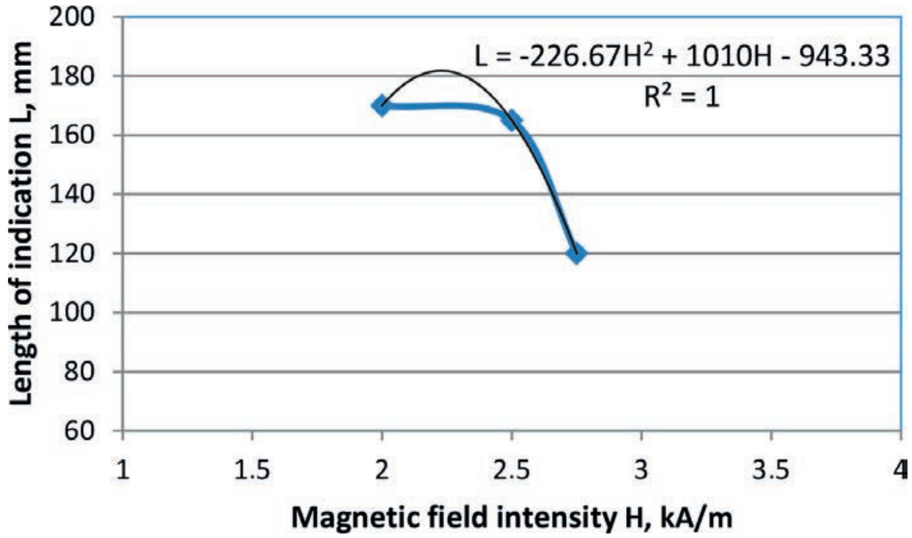

Fig. 16. Correlation between lengths of indications and values of magnetic field intensity in relation to the area of highest sensitivity

magnetic field intensity), testing sensitivity was very high. In addition, the aforesaid range overlapped with the lower limit of data recommended in the PN EN ISO 17638 standard, i.e. values of magnetic field intensity restricted within the range of 2 kA/m to 6 kA/m [13, 16].

The highest testing sensitivity in relation to the test joint was restricted within the range of 2.0 kA/m to 2.5 kA/m. Above a value of 2.5 kA/m, the testing sensitivity decreased. In relation to 3 kA/mm, the level of testing sensitivity was very low, whereas in relation to 4.0 kA/m and above, the level of testing sensitivity was extremely low and precluded the detectability of any indications.

Figure 16 presents the correlation between lengths of identified indications and values of magnetic field intensity within the highest sensitivity area, i.e. where lengths of indications exceed 70 % of the maximum value. The identified trend line enables (with high reliability) the identification of appropriate magnetic field intensity. For this reason, an indication length of 120 mm was attributed to a magnetic field limit value of 2.75 kA/m.

The above-presented analysis and test results confirmed the assumption that an increase in magnetic field intensity was accompanied by decreasing sizes of indications and their detectability. It should also be noted that the above-presented test results and diagrams refer to a specific welded joint made for the purpose of this study. Joints characterised by different dimensions require the performance of other analyses. In addition, it should be emphasized that, as regards magnetic field intensity $H \leq 2$ kA/, the PN EN ISO 17638 standard excludes the above-presented range of values as the level of indication recording in relation to elements subjected to tests. The tests performed for the purpose of this study revealed that the above-presented range enabled the detection of discontinuities in relation to joints of specific dimensions. Any indications of discontinuities, the dimension of which is greater than 2 mm in relation to acceptance level 2X, are, in accordance with appropriate standards, treated as unacceptable [14, 16].

Summary

The above-presented tests and results confirmed the detectability of lacks of penetration in T-joints with fillet welds. The tests also enabled the identification of parameters crucial for the effectiveness of detection. At the same time it could be stated that the magnetic particle testing method made it possible to identify lack of penetration in T-joints with fillet welds after satisfying appropriate requirements and using appropriate testing parameters. The identification of indications in the magnetic particle tests of T-joints with fillet welds was possible in relation to limit value *a* of the penetration run having a boundary dimension of up to 3 mm. The above-presented test conditions could also be used to assess subsequent (i.e. filling) runs in multi-run welded joints with fillet welds. The application of magnetic particle tests in the detection of lacks of penetration (i.e. internal imperfections) in T-joints with fillet welds should ensure the more effective assessment and, consequently, the higher safety of operated structures.

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