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# Influence of lack-of-fusion defects on load capacity of MAG welded joints

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## Abstract

Pressure vessels operating at elevated temperatures and pressures are made of creep resisting plate and welded from individual components using the MAG welding process. The paper proposed focuses on the occurrence of lack-of-fusion defects in MAG welded plate components of pressure vessels. Lack of fusion, which is a planar defect and is, therefore, difficult to detect by common NDT methods, can result in catastrophic consequences since the latter do not only damage a pressure vessel but also jeopardize the environment and workers' health.

The present paper deals with a research on the influence of a welding speed in welding of plate components made of S235JR steel of 8 mm in thickness, special care being taken to deliberately produce lack-of-fusion defects and possibly other weld defects.

Test pieces prepared so as to contain various lack-of-fusion defects were subjected to destructive tensile testing. The force required for a weld failure was compared to actual weld defects. In the test pieces produced with lower welding speeds, a failure occurred in the welded joint and along a lack-of-fusion defect. In the test pieces produced with higher welding speeds, however, a fracture occurred outside a weld, although lack of fusion was present in the weld. Parallel to the tensile tests, radiographic examinations of lack-of-fusion defects were conducted and relevant micro sections were analysed.

The aim of the study conducted was to elaborate a guideline for quality welding of plate components of pressure vessels.

**Keywords**: MAG welding speed, lack of fusion, defects, tensile test, radiographic examination.

## 1. Introduction

In non-destructive testing of pressure vessels, detection of lack of fusion in welds is the greatest challenge. Lack-of-fusion defects are planar defects in welds occurring when a parent metal cannot melt properly and, consequently, the filler material melted attaches itself to a previous weld bead or side walls because it can melt the parent material only partly, which means there is no mixing of the parent metal and the filler material. Lack of fusion is a hidden defect, which is extremely risky when systems such as pressure vessels are subjected to either permanent static load or dynamic load. Because of lack of fusion, leakage may occur and the vessel content may jeopardize the environment and persons in its vicinity. A most frequent cause of the occurrence of lack of fusion is an improper welding technology specified, i.e. a choice of incorrect welding parameters.

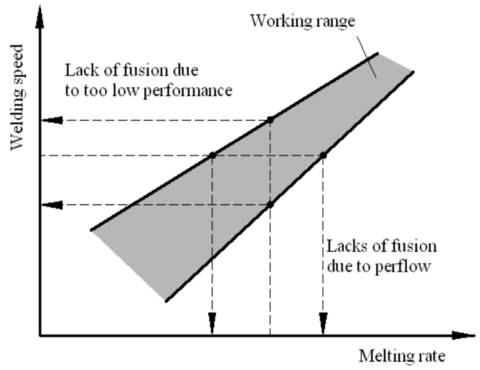



*Fig. 1. Range of limited welding speed [4]*

Most frequently the occurrence of lack of fusion due to an improper welding technology can be attributed to an improper preparation of a weld groove, an incorrect torch inclination, an improper welding position, and possible draught [1]. A second group of causes includes insufficient energy input to the weld area. It has been confirmed that it is highly important to choose optimum welding parameters such as welding current, wire feed rate, and arc length[2].

The welding speed has a major influence on energy input [3]. A high welding speed will provide a lower energy input per unit of length of a welded joint, which will result in insufficient melting of the parent metal, a risk of occurrence of lack of fusion, and unsound welds. A presentation of the dependence of the melting rate on the welding speed indicates that in MAG welding (Fig. 1) the range of sound welds will get narrower with increasing welding speeds. Consequently, limiting values of welding speed with the chosen welding parameters, with which lack of fusion occurs, should be known. With a welding speed lower than the limiting one, a sufficient energy input and satisfactory weld quality can be provided in a considerably larger range of welding speeds, the rate of weld feed speed being same. It is important to know that lack-of-fusion defects, however, may occur also with welding speeds lower than the limiting one, because a larger volume of the molten filler material runs ahead of the welding arc without control[4,5]. A too large volume of the molten filler material prevents the droplets formed to melt the parent metal, thus also preventing mixing of the parent metal and filler material. In this way a "cold joint", i.e. lack of fusion will occur. The molten pool of the filler material can oxidize, thus producing oxides and dissolved gas in a weld. Macro sections of a weld will show the presence of impurities and gases, gas pores entrapped between the parent metal and filler material. Testing of welds showed various types of lack of fusion. We called them black and white lack-of-fusion defects [6,7,8]. The studies made have confirmed that with higher welding speeds the volume of the molten filler material will decrease, which shows in a smaller number of lack-of-fusion defects. The lower limiting value of welding speed, which reaches to the shaded area, is closely related to the melting rate of the filler material and time of dropping of a droplet to the weld area. With a higher limiting welding speed the melting rate will increase. Increasing of the lower limiting welding speed will produce narrowing of the area with sound welds; therefore, a welding process will be more exacting in order to prevent lack of fusion [9,10,11].

## 2. Goals of testing

Lack of fusion in a weld under permanent static loading constitutes a great risk of weld yielding and lack-of-fusion expansion, and, in turn, creeping of a structure. Lack-of-fusion defects are, therefore, treated as discontinuities in a material or even as a crack leading, under permanent loading and after crack propagation and opening, to a final structure failure.

The investigations conducted have confirmed that the occurrence of lack of fusion considerably lowers the load capacity of a permanently statically loaded structure.

A reduced load capacity of a welded joint under the same permanent static loading predicts a shorter life of such a structure.

Detection of lack of fusion in welds is not an easy thing to do due to its planar orientation and location within the weld. Testing performed is to determine the capability of ultrasonic (UT) and radiographic (RT) examinations to detect lack of fusion. It will also be shown what kind of results may be expected with computer tomography (CT). Finally, the occurrence of lack of fusion in the weld will be confirmed with metallographic examinations.

## 3. Welding

Workpieces were prepared with an automatic MAG welding device having a mobile table permitting changes of the welding speed. The parent metal chosen was structural steel S235JR of 8 mm in thickness. The plate used had 200 x 300 mm in size. The filler material used was welding wire G3Si2, and shielding was provided with a shielding gas mixture of 82%Ar + 18% $CO_2$ .

The plate was provided with trapezium notches of 4 mm in depth and with an angle of a side of 60° in order to simulate the first bead. The welding parameters were chosen on the basis of the Taguchi parametric method. Fig. 2 shows welding at a mobile table, which permitted to change the welding speed in a range from 2.0 to 3.1 mm and movement of 0.1 mm/s. In this way 12 welding parameters were chosen, 12 different welded joints and as many workpieces were produced. Other parameters were kept constant to make assessment easier. The welding voltage was 22.8 V, welding current 210 A, gas flow13 l/min, wire extension 18 mm, and wire feed rate 105.27 mm/s. In the weld root there was a water-cooled copper backing, a water temperature being 8 °C. A welding position used was PA, and a constant torch inclination was 14° forward.

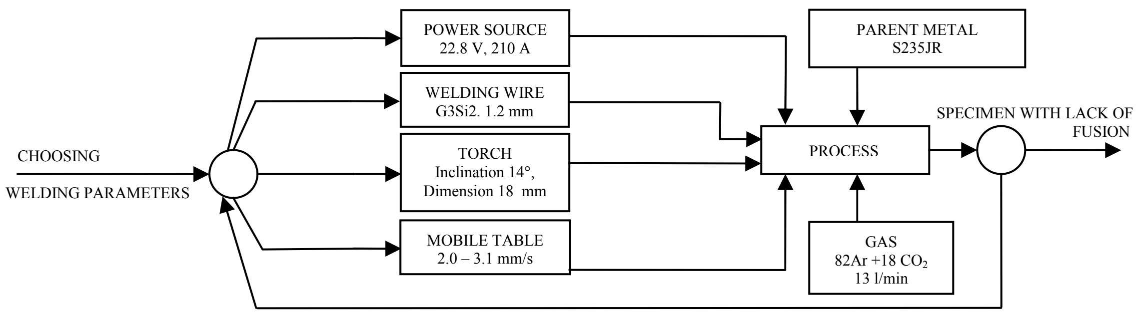



*Fig. 2. Scheme of welding process*

## 4. Testing and test results

It is very important how welded specimens containing lack-of-fusion defects of different location and size are prepared. Although the outer appearance of the welds is nice, the weld can contain planar defects of different size occurring locally or along the entire specimen length. Consequently, a suitable method of detecting hardly detectable lack of fusion should be chosen.

*Ultrasonic testing* was performed to find its suitability for the detection of lack of fusion. Two plates with lack of fusion were tested. The first specimen was produced with a welding speed of 2.3 mm/s, and the second with 2.8 mm/s. Two ultrasonic probes (60° and 70°) were used at both sides of the welded joint (A and B) (Fig. 3, left), the respective probes being placed at a distance $x_1$ and $x_2$. Tests were used to determine the lack-of-fusion location (distance from probe X and depth in the weld D) and size.

2.3/60° 2.8/60°

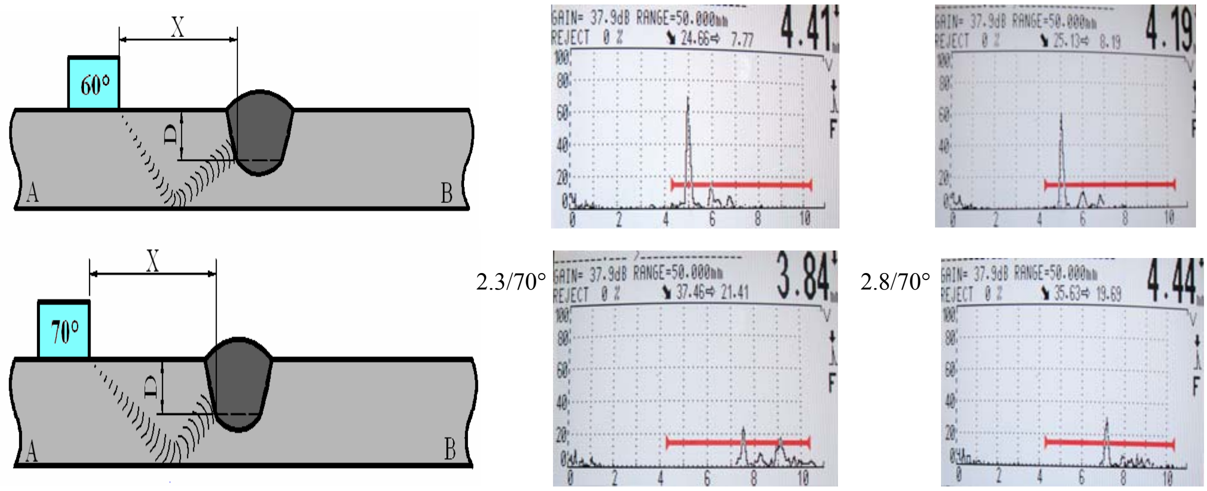



*Fig. 3. Ultrasonic testing of weld and determination of lack-of-fusion location and size*

In all cases ultrasonic testing confirmed lack-of-fusion defects in the weld in a depth of 4 to 5 mm, which means that lack of fusion is most distinct at the groove end. Sound amplification was 37.9 dB and was constant so that the sizes of reflection signals could be compared. Fig. 3 shows four echograms produced with two specimens tested with two different probes, i.e. MWB 60-4 and MWB 70-4. It was found that the signals obtained with the 70° probe were poorer, which is understandable since the groove angle was 60°. The echograms (right, above) indicate lack-of-fusion defects produced at welding speeds of 2.3 mm/s and 2.8 mm/s (60° probe) respectively, and the echograms (right below) the ones produced with welding speeds of 2.3 mm/s and 2. 8 mm/s (70° probe). Table 1 gives results of measurements:

*Table 1. Results of ultrasonic testing of welds*

| **dimension** | $X_{60}$ | | $D_{60}$ | | $X_{70}$ | | $D_{70}$ | |
|---|---|---|---|---|---|---|---|---|
| **position** | A | B | A | B | A | B | A | B |
| **v = 2.3 mm/s** | 7.77 | 6.54 | 4.41 | 5.07 | 20.54 | 21.41 | 4.14 | 3.84 |
| **v = 2.8 mm/s** | 8.19 | 7.51 | 4.19 | 4.55 | 19.69 | 21.66 | 4.44 | 3.76 |

Both methods, i.e. ultrasonic testing and radiographic testing, indicated the presence of lack-of-fusion defects in the weld, the two complementing each other. Consequently, testing of e.g. pressure vessels should be performed with both of them to confirm a defect, its size and, in turn, possible premature structure failure.

*X-ray method.* In X-ray testing the lack-of-fusion defects were transmitted to a radiographic film using a Yxlon Smart 200 device, a tube voltage of 140 kV, a tube current of 4mA, a source-to-film distance of 700 mm, and a focal-spot size of 1,6 IEC 336. Time of exposure was 110 seconds. Several indications of lack of fusion were found. They can be continuous along a specimen or periodic dotted lines along the weld. One of the indications of the occurrence of longitudinal gas pores due to entrapped and dissolved gases from the air. Because of high cooling and solidification rates the gases could not escape but persisted in the material as pores. Both defects, lack of fusion and pores, have a similar unfavourable influence on weld quality. X-ray images were used. Indications confirmed the occurrence of lack of fusion in all the welds produced. The indications shall be evaluated for each case separately. A radiographic analysis confirmed that with lower welding speeds all the welded specimens showed explicit linear lack of fusion. With an increasing welding speed, other parameters being kept the same, these lines become less explicit and they gradually become longer and shorter discontinued lines.

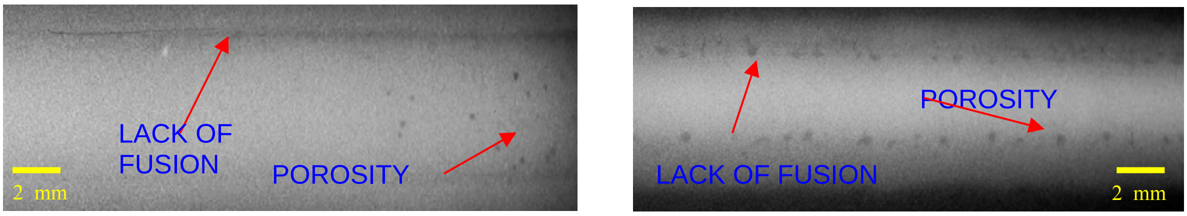
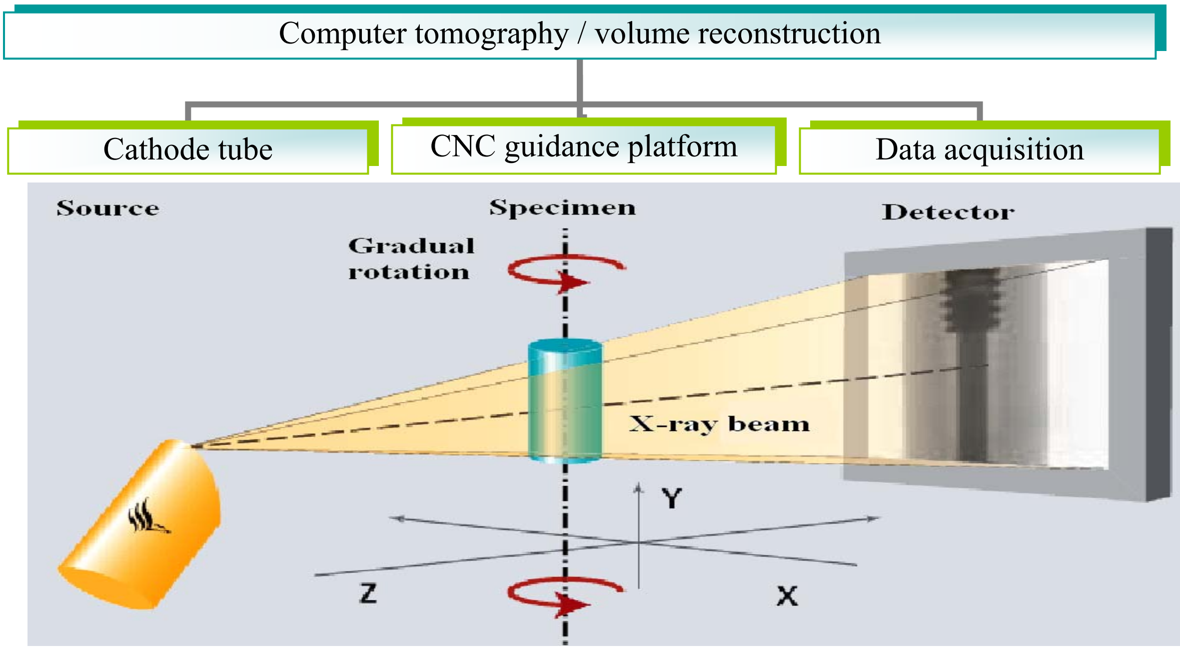



*Fig. 4. X-ray images of welds 2.3 (left)  and 2.8 (right)*

Fig. 4 shows two radiograms of welds produced with different welding speeds, other parameters remaining unchanged.

*Computer tomography* (CT) is a new non-destructive testing method, which has become established lately particularly in detecting imperfections in metal products. 3D images produced with microfocus computer tomography are based on 2D segment specimen projections obtained by gradually rotating the specimen examined in a directed X-ray beam The specimen is rotated gradually with increments of 1° till the entire specimen has been irradiated. This is schematically shown in Fig. 5. The individual segment projections comprise data on the position and density of the beams absorbed in the specimen. The data acquired are then used for a numerical reconstruction of space data and indication construction.  The image reconstruction of a specimen containing imperfections is performed for 3D filtered segment projections.




Because of a limited irradiation source power, specimens for the CT examination were cut as cubes with a side of 15 mm in length. The test specimen was taken from the location in a weld which was already examined, and RT indications confirmed that there was lack of fusion. The specimens prepared were CT tested using a CT system NANOMEX of German Phoenix X-ray company. The system operates with a voltage of 160 kV, a nanofocus X-ray tube, and 16-bit detector with a voxel of 16 µm. In specimen testing a tube voltage of 140 kV and a current of 70 µA were used. The following space and planar images of the two specimens clearly show lack of fusion.

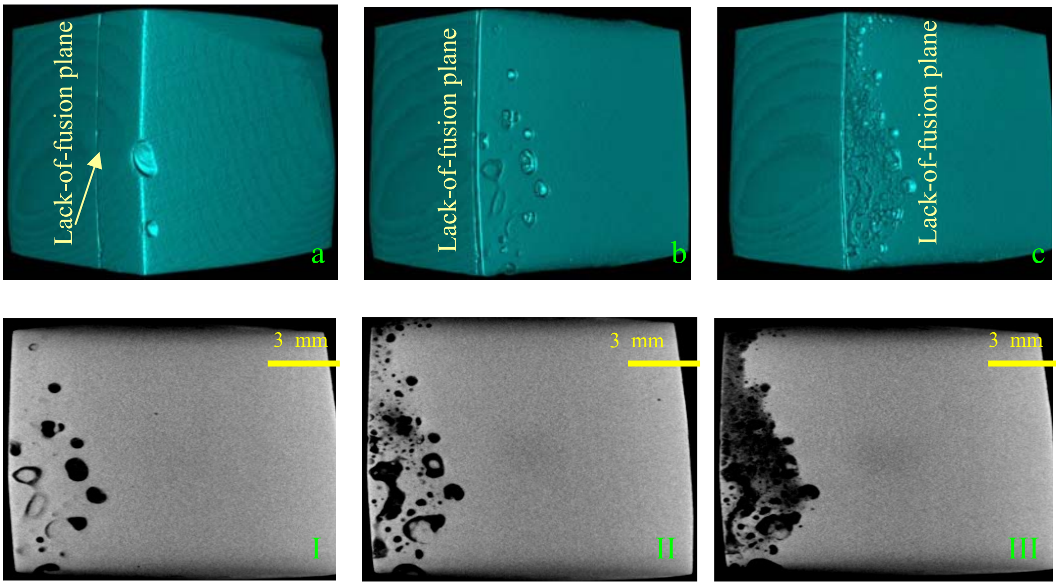



*Fig. 6. Space (a,b,c) and planar CT images* (I, II, III) *of lack of fusion.*

In Fig. 6 the first three images show a space tomogram of various cross-sections of the same specimen. Image (a) is a 3D specimen image showing outside faces and line of the welded joint, in which there is lack of fusion. Image (b) shows a sector of a plane located right before the plane of lack of fusion. There are pores produced during welding due to shielding-gas entrapment. Image (c) shows a sector located right in the lack-of-fusion plane. There are smaller pores and traces of a molten-pool attaching to a cold parent metal. The lower three images (I, II, III) are projections of three different sectors of the same specimen (parallel to the lack-of-fusion plane).

## 5. Macro sections

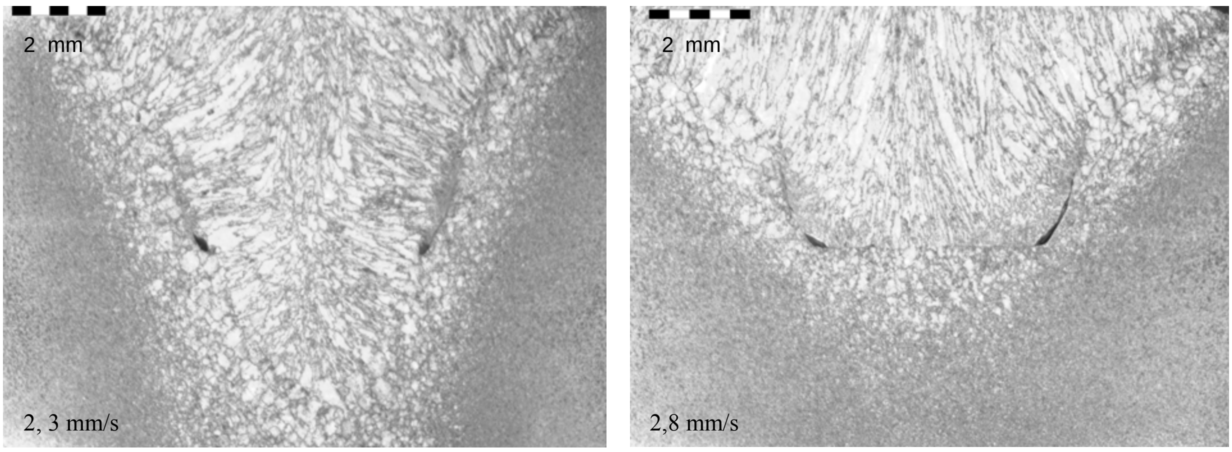



*Fig. 7. Comparison of macro sections obtained with different welding speeds*

Fig. 7 shows two macroscopic images of welds produced with two different welding speeds, which resulted in two different lengths of lack-of-fusion defects. The two specimens were subjected to two non-destructive methods, i.e. UT and RT. it turned out that lack-of-fusion defects occurred in both welds. The weld produced with a welding speed of 2.3 mm/s (left) shows that there was dilution between the parent metal and the filler material, which is confirmed by a flow of diffusion processes crossing the line of the weld groove. This means that fusion of the parent metal was not strong enough, a reason being a large volume of the molten pool running ahead of the arc, filling the entire groove and preventing melting of groove edges, which results in lack of fusion. At the same time a large volume of the molten pool provides high heat input, which enables cross-sectional penetration and remelting of the lower groove side. The weld produced with a welding speed of 2,8 mm/s (right) contains a smaller volume of the molten pool, which fills the lower groove section. At the upper groove section, because of secondary penetration, the parent metal will melt, grains will grow over the groove limit; therefore there are no conditions giving rise to lack o f fusion. Lack of fusion occurs only at the lower groove section where there is no access for the arc and no edge melting. Because of a smaller volume of the molten pool and lower temperature gradient there was no fusion of the lower groove edge.

## 6. Conclusions

The quality of a welded joint has a major influence on the load capacity of welded pressure vessels. The most risky defects are lack-of-fusion defects. They should be detected already during a manufacturing process and immediately repaired. If welding parameters (welding current, welding voltage) are correctly chosen, lack-of-fusion defects are primarily a result of inadequate welding speed. Low welding speeds result in a too large volume of the molten pool in the weld groove, which hinders melting of the weld faces. Non-destructive testing of experimentally produced lack-of-fusion defects gave reliable information on size, location and character of lack of fusion. The radiographic method can confirm the occurrence of lack of fusion in a weld, but not its location and size. In the lack-of-fusion defects obtained with lower welding speeds indications take the form of continuous lines whereas those obtained with higher speeds take the form of spot defects arranged in a line. Ultrasonic examinations, using different angle probes, provided more reliable results on the location of lack of fusion in a weld and its approximate length.
Most information on the character of lack of fusion can be obtained with segment images obtained with computer tomography (CT). 2D and 3D images provide information on the shape, location and size of lack-of-fusion defects. The application of this testing method, however, is limited by the specimen size; therefore, it is suitable only as a complementary method to an analysis of conditions after welding when lack of fusion occurs in the weld.
Macrographs can confirm the occurrence, shape and size of lack-of-fusion defects. To this purpose a series of macrographs obtained with gradual grinding and analysed after each grinding operation can be very helpful. A study showed that a reliable detection of lack of fusion in welded assemblies, i.e. structures, particularly pressure vessels, always requires double examination, i.e. RT and UT, to reliably confirm the size and risk of the indications obtained in the weld.

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