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NON-DESTRUCTIVE TESTING OF DISSIMILAR WELDS COMPARISONS AND PERFORMANCES

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Abstract: *Dissimilar welded joints are widely used today in the industrial field for meeting ever-evolving engineering requirements. The potential problems arising from joining different materials highlight the need to perform thorough testing. By studying a particular case, the paper establishes a link between the parameters of the welding regime and the method or combination of methods (NDT testing) that can lead to the identification of the imperfection generated by their alteration.*

Keywords: *dissimilar welds, non-destructive testing, visual testing, dye penetrant testing, ultrasonic testing, phased array testing, radiographic testing.*

1. INTRODUCTION

Dissimilar welds are characterized by structural and mechanical complexity, which reduces the detection of defects and discontinuities when using conventional inspection methods. Most dissimilar welds have a complex microstructure. In addition, there is also a high level of residual stress (characteristic of these types of joints) that cannot be removed by post-weld heat treatment.

Non-destructive testing is an integral part of all production stages. The main objectives of NDT are:

- Ensuring product reliability,
- Avoiding breakdowns,
- Preventing accidents,
- Increasing profits [1].

Performance evaluation of non-destructive testing applied is based on the most important characteristics of the defects found in the welded joints:

- Defect type,
- Defect dimension,
- Defect position.

Regarding defect position, indications should be classified as longitudinal or transversal discontinuities, judging by their largest dimension relative to the weld's *x* axis, as shown in Fig. 1.

According to their placement, welding imperfections are classified into:

- Internal imperfections (fully or partially contained by the joint section);
- External imperfections (on the surface of the weldment).

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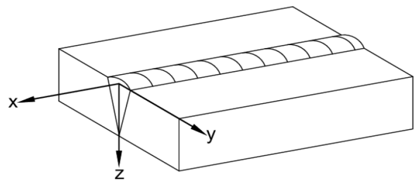


Fig. 1. Axes in the welded joint.

According to their shape, welding imperfections are classified into:

- Plane imperfections,
- Volumetric imperfections.

2. EXPERIMENTAL PROCEDURE

2.1. Probe description

For the experimental procedure, a butt-welded joint was prepared using 3 different welding procedures of the MAG welding process. The weld was then examined with the following methods: visual testing (VT), dye penetrant testing (PT), ultrasonic testing (UT), phased array testing (PAUT) and radiographic testing (RT) – both gamma and X rays.

The base metals welded for the probe (coded as PROBA 1 I.E.Y) were used in the form of steel plates of different alloy trademarks: S235 JR and X12CrMo5, with the following dimensions: 200 × 150 × 9 ($L \times l \times h$).

2.2. Base material study

To determine the chemical composition and mechanical proprieties of the base materials used, they were subjected to an optical emission spectroscopy (OES).

OES is a common form of spectroscopy used to determine elemental components in solid metal samples. It is invasive (non-destructive) and widely used in metal production facilities because it analyzes a vast range of elements with high precision and accuracy.

Based on the result, the following base materials were used: S235 JR and X12CrMo5.

2.3. Welding method

The welding of the two materials was done using the following:

- Base materials utilized: S235JR and X12CrMo5 metal sheets, 9 mm thickness;
- Welding process utilized: GMAW (MAG);
- Filler material utilized (EN 14341-A): G 46 4 M21 4Si1Ș;
- Shielding gas utilized: M21Ș;
- Joint preparation: Single-V preparation by mechanical machining, (α = 60 °, b = 4 mm, according to EN ISO 9692-1:2014).

The joint opening of 4 mm makes the welding technique fall into the category of narrow joint welding. The notion of "narrow joint welding" brings together a series of variants of electric arc welding processes (MIG-MAG, WIG or SF) characterized by the fact that the welding is performed with a much smaller opening than the one corresponding to the process from which they resulted. The main difference between narrow joint welding and the welding process from which it was derived is the technique used to introduce the wire and gas (in the case of MIG-MAG welding) into the joint.

Because of this, a difficult problem is represented by inserting the wire into the joint without accidentally touching its wall. Added to this is the fact that it is necessary to ensure a lateral penetration into the base metal at a correct positioning of the wire, without being able to observe the electric arc. Most of the time, due to economic advantages and increased productivity, welding is done with a single pass per layer (as in the case of the reference sample – PROBA 1 I.E.Y) [2].

Given these conditions, the appearance of possible defects characteristic of this category of welded joints must be considered. Typical defects in narrow joint welding are:

- Lack of fusion between base and filler materials;
- Hot cracks;
- Porosity;
- Undercuts.

The welding seam was delimited in three equal zones (zone 1, 2 and 3) with different welding regimes. This was done to establish a link between the parameters of the welding regime, the type of imperfection generated and the examination method (or combination of examination methods) necessary for identifying them. The parameters of the welding regimes corresponding to each zone are listed in Table 1.

Parameters corresponding to the first welded zone represent the correct welding regime. Imperfections are not expected to occur in this section. However, imperfections caused by the welding technique are an exception.

The welding of the second welded zone was done after reducing the shielding gas flow rate (by approx. 6 l/min.). Because of this, the appearance of porosity both in the volume of the weld seam and on its surface is very likely.

Table 1

Welding parameters corresponding to the 3 welded zones

Zone 1	R	I_s	124 A	Shielding gas flow rate = 17 l/min.
		U_a	21–23 V	
		V_s	100 mm/min.	
	F	I_s	128–130 A	
		U_a	21–23 V	
		V_s	100 mm/min.	
	C	I_s	130 A	
		U_a	21–23 V	
		V_s	100 mm/min.	
Zone 2	R	I_s	124 A	Shielding gas flow rate = 11 l/min.
		U_a	21–23 V	
		V_s	100 mm/min.	
	F	I_s	128–130 A	
		U_a	21–23 V	
		V_s	100 mm/min.	
	C	I_s	130 A	
		U_a	21–23 V	
		V_s	100 mm/min.	
Zone 3	R	I_s	90 A	Shielding gas flow rate = 17 l/min.
		U_a	21–23 V	
		V_s	100 mm/min.	
	F	I_s	80 A	
		U_a	21–23 V	
		V_s	100 mm/min.	
	C	I_s	136 A	
		U_a	21–23 V	
		V_s	100 mm/min.	
where: *R – root pass, F – filler pass, C – cap pass,* *I_s – welding current, U_a – voltage, V_s – welding speed*				

For the third welded zone, the shielding gas flow returned to the initial value, but the value of the welding current intensity was changed (it was decreased by values between 30–50 A).

2.4. Non-destructive testing

After welding, the reference sample was tested using multiple methods: visual testing (VT), dye penetrant testing (PT) and ultrasonic testing (UT) and radiographic texting (RT) both with gamma and X radiations. The results of these examinations are listed in Table 2.

The consequence of this change is the very likely occurrence of lack of root penetration and/or lack of fusion in the welded seam volume or in the root pass.

The welded joint in its final form is presented in the Fig. 2.

a b

Fig. 2. Reference sample: *a* – cap side; *b* – root side.

Table 2

Non-destructive testing results

Visual testing (VT)		
Zone 1	R	Overlap
Zone 2	F	Poor restart
		Clustered porosity
		Intermittent undercut 1
	R	Lack of (root) fusion
Zone 3	F	End crater pipe
	R	Incomplete root penetration
		Excess penetration
		Sagging
Dye penetrant testing (PT)		
Zone 2	F	Intermittent undercut 2
		Intermittent undercut 3
		Intermittent undercut 4
		Clustered porosity
	R	Lack of (root) fusion
Zone 3	R	Incomplete root penetration
		Intermittent undercut 5
		Intermittent undercut 6
Ultrasonic testing (UT)		
Zone 1	F + R	Crack
Zone 2		Clustered porosity 1
		Lack of side wall fusion
		Clustered porosity 2
Zone 3		Incomplete root penetration
Radiographic testing (RT)		
Zone 2	F + R	Clustered porosity 1
		Clustered porosity 2
		Intermittent undercut 1
		Gas pore
Zone 3		Incomplete root penetration
		Lack of (root) fusion
		Intermittent undercut 5
		Intermittent undercut 6
		Excess penetration

3. COMPARATIVE STUDY OF THE APPLIED EXAMINATION METHODS

After applying all non-destructive testing methods on the reference sample and evaluating the results by comparison, the following conclusions cand be drawn for each method.

3.1. Visual testing (VT)

- Offers conclusive indications regarding defect's type only if they are positioned to the surface of the weld. As defects position deeper into the welding seam, they become harder to identify. This method failed to highlight the intermediate undercuts (2–6) even though the discontinuities communicated with the surface.
- Offers conclusive indications regarding defect's size only if they are positioned to the surface of the weld. If the discontinuities also extend on the *z* axis the indications lose their relevance to the point where they become inconclusive.
- Offers conclusive indications regarding defect's position only if they are positioned to the surface of the weld. For open surface defects indications lose their relevance to the point where they become inconclusive. This method failed to accurately determine the position of the clustered porosity (zone 2), even though the defect was visible on the surface.

We can say that visual examination plays an important role in determining the type, size and position of defects on the surface of the weld. It should also be noted that among all the examination methods, it is the only one that provides indications about this category of defects. The limitation of the method is caused by its dependence on the position of the defect and the fact that its performance is closely related to the experience of the operator (because it has a high degree of subjectivity in interpretation).

3.2. Dye penetrant testing (PT)

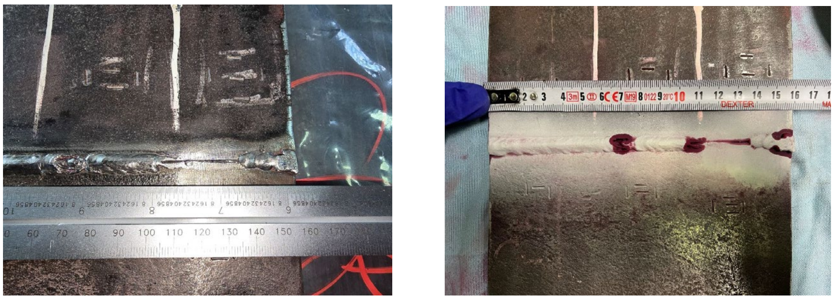
- Offers conclusive indications regarding defects open to the surface. When the defect is not discontinuous, the method does not generate any indications. This method failed to highlight defects such as: overlap (zone 1), poor restart (zone 2), end crater pipe, excess penetration and sagging (zone 3).
- Offers less conclusive to inconclusive indications regarding defect's size.
- Offers conclusive indications regarding defect's position. When it comes to defect position, dye penetrant testing accurately indicates the *x* and *y* axis coordinates of the defect but is limited when it comes to the z coordinate of the defect, providing imprecise information about it.

It is safe to say that dye penetrant testing (PT) is complementary to visual testing (VT) because it highlights the defects that communicate with the surface but becomes inconclusive for the defects located entirely on it. This fact represents the limitation of the examination method [4–6].

A good example of the complementary relationship of the two examination methods is represented by the excess penetration + sagging combination and the two intermittent undercuts, all found in the third zone of the welded seam. Visual testing (VT) provides conclusive information for determining the type, size and position of excess penetration + sagging combination but becomes irrelevant for highlighting the intermittent undercuts positioned exactly below them (Fig. 3a). On the contrary, dye penetrant testing (PT) highlights the intermittent undercuts but gives no indication of excess penetration + sagging defects (Fig. 3b).

3.3. Ultrasonic testing (UT)

- Offers conclusive indications regarding defect's type in the welded seam volume. Despite this fact, in case of overlapping defects (of the same type/different types) the examination method becomes limited [3]. This method failed to highlight the intermediate undercuts (2, 3) and the lack of (root) fusion, all positioned in the second zone of the weld, because their indications overlap with the indications



a b

Fig. 3. VT and PT comparison: *a* – VT; *b* – PT.

corresponding to the cluster porosity defect. Also, the lack of root fusion and the intermediate undercuts (4, 5) positioned in the third zone of the weld were not identified because their indications overlap with the indications corresponding to the lack of root penetration. It is very important to underline the fact that this examination method is the only one (among those used) that was able to identify the crack that appeared in zone 1.

- Offers conclusive indications regarding defect's size.
- Offers conclusive indications (and more precise) regarding defect's position (for volumetric defects only). This method accurately determines the position of the identified defects on all three axes (x, y, z). It should also be noted that, of all the examination methods, it is the only one that is conclusive for the defect's position on the z axis.

Because ultrasonic testing was the only method able to highlight the crack located in the first zone of the welded seam, this area (assumed to be free of defects because it was welded with the appropriate parameters) was further analyzed with an advanced examination method, derived from the classical one – Phased Array Ultrasonic Testing (PAUT).

PAUT, also known as phased array UT is an advanced non-destructive inspection technique that uses an array of ultrasonic test probes (UT) made up of numerous small elements. Each of these is individually pulsed with computer-calculated timing to create the staged appearance of the process, while the matrix refers to the multiple elements that make up a PAUT system. The beam from a phased array probe can be focused and electronically "swept" across an inspection part without moving the probe itself. This differs from single element probes (also known as monolithic probes). These more conventional probes must be physically moved or rotated to cover larger areas, which is not necessary for PAUT. Each element radiates a spherical wave at a specified time, creating waves that converge and diverge to create a nearly plane wavefront at the specified location. Changing the progressive delay allows the beam to be electronically directed and "swept" through the test material like a reflector. When multiple beams are assembled, a visual image is created that shows a "slice" through the test object. This means that only one transducer is needed to inspect components at different angles. Using this type of probes is much faster than using conventional ones, while also displaying cross-sections of the specimen in real time and allowing easier interpretation (Fig. 4).

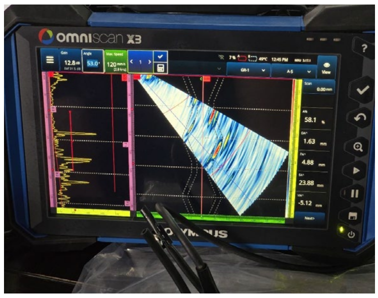


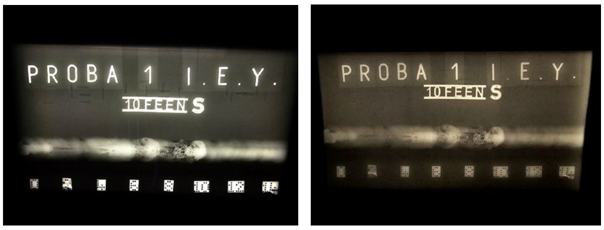
Fig. 4. The crack (zone 1) highlighted by PAUT examination.

This type of examination provides the most accurate and complete information about all 3 important characteristics of the identified defects. Figure 4 shows data such as: the A-scan view, the sectoral view, the angle that best highlights the defect together with its position relative to the shape of the joint (precise coordinates).

Ultrasonic examination (UT), both in the conventional version and in the phased array version, is of great importance in the control of dissimilar welded joints (and not only) because it represents the examination method that can precisely highlight the position of the defects that appeared during welding. In this case, the limitations appear when the defects are positioned overlapping or grouped, at which point the indications become difficult to interpret (especially in the classical examination method) [7–13].

3.4. Radiographic testing (RT)

- Offers conclusive indications regarding defect's type. Examination becomes inconclusive when defects are layered. The method is limited in identifying small discontinuities depending on its sensitivity and the position of the defect. This method (for both gamma and X-ray) does not show the defects hidden below the clustered porosity (zone 2), nor the end crater pipe hidden by the excess penetration and the sagging. It should be emphasized that the radiographic testing does not generate and indication of defect for the crack located in "zone 1". In the case of radiographic testing, regardless the type of radiation, the degree of detectability is low in case of cracks oriented perpendicular to the direction of the beam [14–18].
- Offers conclusive indications regarding defect's size, there being small differences between the two types of radiation used. When examined with gamma rays, the size of the lack of (root) fusion defect is more difficult to interpret, so the indication becomes less



a b

Fig. 5. RT comparison: *a* – X-rays; *b* – gamma rays.

conclusive, so the examination is limited by defect size. It should be stated that the coordinates of the defects on the *x* and *y* axes are the most accurate in this type of examination. For a better distinction, the difference in sensitivity of is shown in Fig. 5.
- Offers conclusive indications regarding defect's position (only on *x* and *y* axis). As stated before, the depth of the defect cannot be determined.

In both cases, the radiations have an electromagnetic nature, the difference between them being the fact that when producing X-rays, the transition is between two quantum states of the electronic shell, and in the case of gamma radiation, the transition is between two quantum states of the atom's nucleus.

When comparing gamma testing to X-ray testing, both advantages and disadvantages can be observed:

The advantages of using gamma radiation compared to X-rays are:
- No power source is needed;
- No cooling system is needed;
- The equipment is compact and easy to transport;
- The radiation spectrum is discrete, and the scattering effect is minimal;
- Gamma radiation has a very high penetrating capacity.

The disadvantages of using gamma radiation compared to X-rays are:
- Radioactive sources must be replaced periodically;
- The radioactive source cannot be turned off;
- The radioactive source must be operated remotely;
- The quality of the radiographic image is poorer;
- Expose time is longer, affecting productivity.

7. CONCLUSIONS

Choosing the ideal control method is a complicated problem that requires taking into consideration aspects such as:
- The constructive particularities of the examined products;
- The nature and physical properties of the materials used for the products;
- The type and location of possible imperfections;
- The particularities of the control methods and the performance of the equipment used;
- The training of the operator.

In most cases, to obtain the most conclusive results, it is necessary to resort to a combination of control methods.

For the experiment, four non-destructive examination methods were comparatively analyzed. They were used for quality control of a dissimilar butt-welded joint made of steel, S235JR and X12CrMo5. S235JR is an unalloyed structural steel and X12CrMo5 is a heat-resistant steel alloyed with Cr and Mo. The two materials have different chemical composition, which is why the joint was called dissimilar.

Magnetic testing was omitted on purpose because the study has a general applicability to dissimilar welded joints. Since we are discussing the likely use of different base materials, there is a possibility that they may not be ferromagnetic, hence the use of all other examination methods.

For dissimilar joints, the use of a reduced number of control methods is not sufficiently precise. Although this approach can bring economic advantages, it does not provide the certainty that the welded joint does not present defects.

In the case of the reference sample – PROBA 1 I.E.Y, the most dangerous type of defect was identified only means of a single control method, the ultrasonic examination (both in conventional and even more so with the advanced method – PAUT). Although the radiographic testing was also used for volumetric testing, it failed to register the crack positioned in the zone which was assumed to be free of defects because it was welded with the appropriate parameters.

Following the comparative study of examination methods, welding conditions and parameters, possible causes of the occurrence of all identified defects can be determined.

Table 3

Causes of the occurrence of identified defects

Defect category	Defect	Possible cause
Shape defects/surface defects	Sagging	Incorrect working position of the electrode
	Poor restart	Deficiencies in arc initiation, interruption, and conduction
	Intermittent undercut	Incorrect working position of the electrode
	Incomplete root penetration	Welding current too low
	Excess penetration	Electrode diameter too small
Internal plane defects	Crack	Incompatibility between the base metal and the filler metal, use of improperly shaped joints
	Lack of (root) fusion	Incorrect placement of welding passes and layers
	Lack of side wall fusion	Low heat input
Internal volumetric defects	Clustered porosity	Low gas flow, poor weld pool protection
	Gas pore	
	End crater pipe	Temperature drop/improper deoxidation of the weld pool

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